GRAPHONOMICS:
Contemporary Research in Handwriting

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PREFACE

Of the two basic language skills, reading and writing, reading has been much more intensively and extensively investigated than writing. This has been evidenced by: (1) the enormous amount of research conducted both in theoretical and applied domains of the subject matter; (2) the publication of numerous books on reading in different languages all over the world; (3) the existence of national and international associations devoted exclusively to the study and promotion of reading, and; (4) the regular publication of various regional, national and international journals to deseminate up-to-date knowledge on findings and conclusions about reading. In contrast, similar lines of development for writing have been, at best, late in coming. Handwriting, as an important component of general writing behaviour, was certainly not given appropriate attention for a long time. However, the situation changed in 1982 when the International Workshop on the Motor Aspects of Handwriting was held at the Department of Experimental Psychology, the University of Nijmegen, the Netherlands.

The Nijmegen workshop, the first conference on handwriting since the Invitational Conference on Research in Handwriting held at the University of Wisconsin-Madison in 1962, brought together scientists from such diverse disciplines as experimental psychology, bio-engineering, neurology, education, and computer sciences. Being a highly successful event, the Workshop highlighted the common urge to treat handwriting research as a multidisciplinary science (see Thomassen, Keuss and Van Galen (ed.), *Motor Aspects of Handwriting*, Amsterdam: North-Holland, 1984). During the Workshop week, an informal coinage of the word *Graphonomics* was greeted with enthusiastic reception by participants as a unifying concept to signify the multidisciplinary nature of the new science of handwriting research. However, it fell short of formally pronouncing the birth of *Graphonomics* which became the hope of yet another conference at a later date. It was commonly felt that the success and friendship established in Nijmegen should be continued; but, a definite conclusion was not reached before the participants departed.

The wish for a follow-up of the Nijmegen workshop came a step closer to reality when the senior editor of this volume met Dr. George Stelmach at a reception organized by the American Psychological Association at the International Congress of Psychology, in September, 1984 in Acapulco, Mexico. Our conversation focussed on the likelihood of organizing the next handwriting conference in Hong Kong in 1985 and how it should be organised. The idea was instantly endorsed at the party by Dr. Xu Liancang, Director, Institute of Psychology, Academia Sinica, Beijing. This plan was quickly communicated to colleagues who attended the Nijmegen gathering previously. Soon, in the field an enthusiastic response zoomed in from various centers throughout the world, especially Dr. A. Thomassen and his associates in Nijmegen. So the Department of Psychology, the University of Hong Kong took on the task of organizing the Hong Kong "rendezvous" of *Graphonomists* in summer, 1985.

With a view to broaden the scope of coverage from its Nijmegen predecessor, this conference, the Second International Symposium on the Neural and Motor Aspects of Handwriting, set out to achieve several specific goals. First, it should reflect the growing interests of scientists in handwriting research from a neurolinguistic perspective relating graphic performance and brain pathology. Secondly, the Symposium chose, as one of its emphases, to include research on writing systems that are outside of the Western language systems. Studies using the Chinese and the Japanese orthographies would serve not only to test; but, explore contemporary research unlikely to be generated by studies only conducted in English writing system. This provided an interesting regional character that would have important implications to research in general handwriting behaviour. Thirdly, the Symposium should serve as the venue to explore the possible formation of an international body devoted to the promotion of scientific research in handwriting and graphic behaviour, a need widely felt by some colleagues since the Nijmegen workshop in 1982. Lastly, it should provide an early opportunity for researchers from the various related disciplines to exchange matters of mutual interest and to establish new friendships among themselves.

The Symposium took place as planned in the Department of Psychology, the University of Hong Kong, from July 8-12 1985 with the opening ceremony formally officiated by Professor Rosie T.T. Young, Pro-Vice Chancellor of the University. It was attended by over 40 researchers from 13 countries around the world. After five days of intensive schedule, it successfully achieved all of its envisaged missions. The International Graphonomics Society was formally formed on July 11, 1985 at the University's Convocation Room with a eight-member international Executive Committee duly elected. (See Appendix II of this volume for a brief account of the genesis, goals and activities of the International Graphonomics Society.) The present volume comprises selected and revised papers presented at the Second International Symposium in the Neural and Motor Aspects of Handwriting. As the contents of the book reflect, the East Asian regional character, which was a major attraction of the conference, was illuminated in a number of papers using the Chinese and Japanese languages as targets of handwriting research. The multidisciplinary nature of the Symposium could not be better portrayed than by the diversity of presentation of its proceedings in such area as psychonomics, education, neurology, linguistics, computer science, biophysics, methods engineering, and speech science.

The present volume, another product of the Symposium, is divided in the following five sections:

Section One.	Motor Theory in Handwriting Research
Section Two.	Development and Learning of Handwriting Behaviour
Section Three.	Modelling and Analyses of Handwriting
Section Four.	Memory and Cognitive Processes in Handwriting
Section Five.	Neural Bases to Handwriting Research

The selection of papers for inclusion in this book was based on several criteria. First, they must have direct relevance to the theme of the Symposium. Secondly, they should have the quality of a standard comparable to articles for international scientific journals. Thirdly, they should be a study based on empirical or experimental investigations. Lastly, they should contribute significance to aspects graphonomics as an emerging scientific discipline by breaking new ground or expanding existing theories, observations, or conclusions in handwriting research. Each paper was first reviewed by a panel of four referees in joint working sessions. Only those provisionally accepted by this panel were further reviewed for detailed comments. The four members were Drs. G.E. Stelmach, A. Thomassen, G. Van Galen and H.S.R. Kao, who were subsequently assisted by Drs. H.L. Teulings, L. Schomaker, D. Shek, R. Hoosain and N. Murphy in the reading of manuscipts. To all these colleagues, the Editors extend their sincerest gratitude for their valuable contributions to the high quality of this volume. We also would like to acknowledge the privilege, granted by the International Graphonomics Society in the first meeting of its Executive Committee held in China, to proclaim this book the inaugural volume of what promises to be a long series of conference proceedings to be published under the auspices of the Society in the future. To mark the birth of a new scientific discipline as well as that of a new international scholarly society, this book is privileged to bear the title, *Graphonomics: Contemporary Research in Handwriting.*

The preparation of this present volume, a natural continuation of the 1985 Hong Kong Symposium, could not have been made possible without the cooperation and assistance of a number of people involved in the organization of the Symposium. For the Symposium programming, Drs. G. Stelmach, and A. Thomassen helped greatly in our organization by communicating with scientists in North America and Europe about the Symposium and contributed significantly their efforts in support of the scientific program. We would also like to acknowledge our appreciation of many members of the Psychology Workshop under the coordination of Mr. Ho Po-keung for their unfailing technical support throughout the Symposium: Mrs. H.P. Li, Mr. Stewart Lam, Mr. Chow Wai, Mr. Michael Tang, Mr. Cheng Wai-leung, and Mr. Lai Keung. Additionally, Mr. Ho and Mrs. Li are also credited for their excellent art work for the present volume. Our special thanks are due to Miss Jane Lee who ably led the team of office staff consisting of Mrs. Anna Ho, Miss Mimi Lui, Mrs. Teresa Chan and Mr. Chung Sing-kau in handling all aspects of the day-to-day activities of the Symposium secretariate from correspondence, to hotel reservations, tour arrangement and finer details of personal needs of our participants throughout the entire operation. This same team has also been the primary force behind the tedious, editorial work for this present volume. The editors have been fortunate to have worked with this team of most capable clerical staff without whose patience and assistance neither the Symposium nor the book would have been possible. Special thanks are also due to Dr. K. Michielsen, Publisher of North-Holland Publishing Company and Dr. G.E. Stelmach, Editor, *The*

Advances in Psychology Series for accepting this book as a new title in the Series. Finally, the generous support of Dr. Rayson Huang, the Vice-Chancellor of the University of Hong Kong, in all aspects of the Symposium organization, as that given to all previous international conferences organized by its Department of Psychology, is also gratefully acknowledged.

Hong Kong/Nijmegen.
March 29, 1986.

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Overview

This Section includes four papers examining handwriting as psychomotor behaviour. There were a couple of common themes in some of the papers. One, even though the units of analysis may give the appearance of bottom-up processes, was the appreciation of the relevance of top-down processes in the control of handwriting. Evidence was accumulated on central control of the execution of whatever segments of writing that were taken to be the unit of analysis. Thus, along with other indicators of organization, the involvement of central processes may be manifested in interaction of subsystems, contextual effects, and left-to-right (or right-to-left in some languages) differences.

Another common concern was the identification of the production unit in handwriting. There seemed to be agreement that it was desirable to consider a hierarchical structure of components, and the unit of analysis chosen depended on the purpose of both the handwriting task and the investigator. As distinguished from some other sequential behaviours, handwriting appeared to provide more dimensions of analysis, apart from the universal temporal framework of investigation. Perhaps the most important of these was the structural or spatial aspect of handwriting. Even the temporal aspect of handwriting may have unique characteristics yielding important opportunities for investigation.

The study by van Galen, Meulenbroek, and Hylkema attempted to verify a model of mixed linear and parallel processing at two levels: sequential processing at the micro-level and parallel processing at the macro-level. The hierarchical nature of the model attempted to predict which specific elements of the writing tasks were handled earlier by higher rather than by lower levels of information processing. Specifically, effects of word complexity manifested themselves before those of letter complexity, which in turn preceded those of letter connections. Velocity variables in addition to time variables were monitored, in a writing task using artificial words allowing the manipulation of phonemic similarity, length of separate letters, type of letter connection, and word length. Results generally supported both the existence of level specific time boundaries and the hierarchical nature of the levels. It was also noted that writing, by virtue of the slower real time execution speeds of handwriting, allowed a more detailed prediction of real time execution of hierarchical levels, providing a better opportunity to study motor behaviour than speech production.

Teulings, Mullins, and Stelmach in the following paper tried to determine the production unit in handwriting, comparable to the stress-group in speech production and the key stroke in typing. The writing of simple repetitive stroke patterns was used, generating fast and uniform writing sequences. However, in the absence of element duration effects, no clearly defined production units were found. It was suggested that the main distinction of writing production was that the more or less orthogonal movement components involved limited the speed of writing movements. Thus, it was not necessary to prepare more than one stroke in advance. This contrasts with the much faster movements for speech production. The suggestion in separate experiments, that either the down-stroke or the uni-directional stroke was the more likely production unit, indicated the possibility that there was no one single unit but the actual units varied according to the form of the writing output.

Maarse, Schomaker, and Thomassen researched the systematic change in a few variables occurring within written words from left to right. These variables included biomechanical constraints caused by hand rotation during the production of a word. As production progressed from left to right, it was found that the fingers tended to play an increasing role in relation to the hand. However, pointing to a more central effector coordinate system rather than more peripheral executing effector systems, the results indicated intricate interactions between the two subsystems. The subsystems themselves functioned nonlinearly, with the input frequencies being followed only within a certain limited range.

The paper by Kao, Mak, and Lam systematically investigated the variables affecting handwriting pressure as well as pressure variability. A number of factors were manipulated in the empirical study, including control mode (tracing, copying, or freehand), complexity (number and nature of strokes), and stimulus type (line or cursive figures). To establish the cross-linguistic generality of the findings, Chinese-English bilinguals were asked to perform in both Chinese and English. In general, although pressure variability was greater for freehand writing, pressure was greater in the tracing mode A decrease in pressure was associated with increased complexity. This was true for both Chinese and English, even though writing pressure was greater for Chinese. Both handwriting pressure and pressure variability were greater for linear figures when compared with cursive figures. Progressive motion variability was noted throughout these studies. The establishment of these factors in the diverse handwriting situations provided a perspective on handwriting as a cognitive-motor system with a dominant cognitive component.

Graphonomics: Contemporary Research in Handwriting
H.S.R. Kao, G.P. van Galen, R. Hoosain (eds.)

ON THE SIMULTANEOUS PROCESSING OF WORDS, LETTERS AND STROKES IN HANDWRITING: EVIDENCE FOR A MIXED LINEAR AND PARALLEL MODEL

Gerard P. Van Galen
Ruud G. J. Meulenbroek
Henk Hylkema

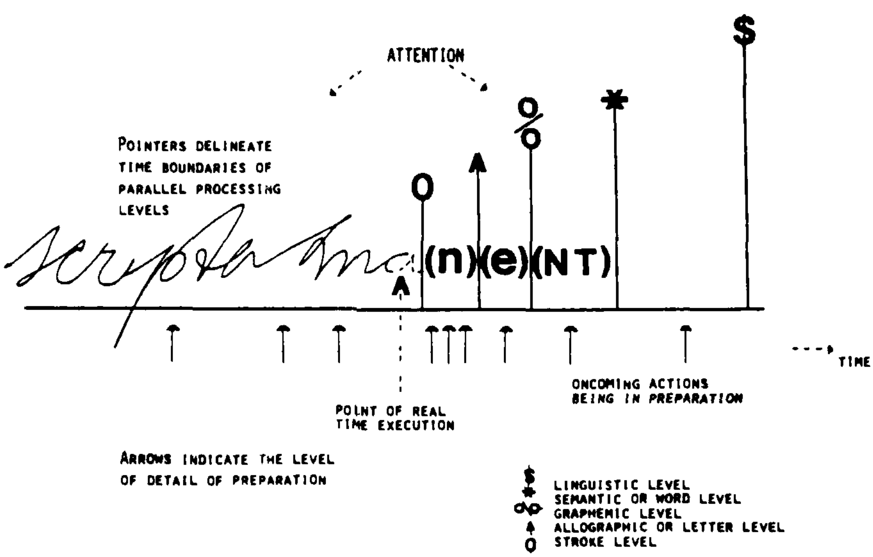
INTRODUCTION

When we observe the writing hand one of the most striking peculiarities is the quasi continuous character of the accelerations and decelerations of the moving pen. Especially with cursive handwriting, and when there is no uncertainty about the text to be written, strokes are delivered in a machine like and regular fashion. Seemingly, strokes follow each other without pauses. New words start after a jump of much less duration than a normal reaction time to start writing words and the difficulty of individual words is not visible at first sight in the form and duration of individual strokes. Human performance theorists would argue that retrieval, programming and execution of words, letters and strokes take place in a parallel fashion. Resources for control of each of these task levels could be delivered from either a common pool, which is only overloaded in heavy task circumstances, or from separate pools which don't interfere with each other because the levels of processing are different (Eysenck, 1982).

Careful studies of the motor programming and execution process, however, have resulted in a more accurate knowledge of the processing demands during ongoing movement. Sternberg, Monsell, Knoll and Wright (1978) proposed the view that motor programming is a hierarchical and dynamic process, which continues after the start of movement. More abstract levels of the programming process are supposed to occur earlier in the timecourse of preparation and execution than the more concrete and context specific 'unpacking' of final details. With a Morse coding task Klapp (1976) brought about evidence for the view that the duration of later elements of a motoric sequence is only programmed in advance as far as it is related to the duration of earlier elements, whereas the exact value of this duration is reflected in the interval of execution time immediately before that later element. Kerr (1975), in a study on the processing demands of a stylus movement task, found that online monitoring of the path of the stylus left less processing capacity for a secondary task. In a study with letter writing tasks, with a paradigm analogous to that of Sternberg, et al. (1978), Hulstijn and van Galen (1983), however, did not find that longer words, which presumably ask for more processing capacity, lead to longer writing time for letters at comparable serial positions within the word. Most of the studies reported so far focus on only one or two dimensions of movement complexity. Sternberg, et al. (1978) studied processing demands of the length of an utterance and the number of syllables within the words of an utterance. Klapp (1976) focussed on length of the Morse code elements and combinations of elements of same and different lengths.

In natural handwriting many processing levels have to be monitored close together in time (Ellis, 1982). Intentions have to be coded in a linguistically and semantically acceptable form. Words are coded in a graphemic code and graphemes are substituted by allographs. Van Galen and Teulings (1983) suggested that from the allographic level on, three motoric stages are responsible for the preparation of the real time execution of the writing task: motor programming, i.e., finding the correct sequence of strokes corresponding with a particular allograph, force i.e., setting the correct overall force level corresponding to the appropriate size of the writing and finally, recruitment of the appropriate muscle groups, depending upon biomechanical and anatomical context. At the micro-level, i.e., with regard to the preparation of individual levels, we supposed that these motoric stages had a sequential, non-overlapping structure. At the macro-level, however, it is unlikely that stages involved in the preparation (and execution) of successive letters and strokes would not overlap. A possible model for sequential processing at the micro-level and parallel processing at the macro level is a system that works simultaneously on the representation of a motor act at more than one level. Figure 1 visualises such a model. The subject in this model is writing the adage 'Scripta manent.' The solid trace represents the part of the task already finished; the dashed trace stands for the mentally prepared but not yet realised, action plan. At the semantic, and in the resent model highest level the rightmost pointer line indicates that the preparation has proceeded to a point after the end of the word under execution. At the same time the lower, graphemic level is working about three graphemes ahead of the writing pen (Van Nes, 1985). Still lower in the hierarchy allograph selection and thus motor programming is only one or two letters ahead (Teulings, Thomassen and Van Galen, 1983) and finally, overall force control and muscle initiation have a place on the time scale immediately prior to real time pen movements. When we consider consecutive points in time in the model, e.g., t1, t2, t3 etc., it is assumed that each of the frontlines of the different processing levels move to the right. That is, future building blocks of the action plan become activated in a form ready to be 'unpacked' (Sternberg, et al. 1978) by lower processing levels. Furthermore it is assumed that pointers delineating the activation of lower levels never cross the frontline pointer of a higher level. The sequential structure of the motor stages stays intact, but at the same time different processing levels are active in a parallel manner with regard to different elements of the action plan.

Figure 1 Visualisation of a control model of handwriting. The writer's pen is at the point of real time execution. Here the solid trace of already finished letters continues as dotted to represent prepared but future strokes. It further continues as the already retrieved cursive allograph 'n' and further as the print letter 'e' representing the next grapheme in preparation. The capitals 'EN' stand for the acoustically encoded end-morpheme of the word. Linguistic processing is still more ahead. Pointers above the time axis indicate that different processing levels are more or less ahead of the point of real time execution. $ = linguistic level; * = semantic or word level; % = graphemic level; ˆ = allographic or letter level; o = stroke level. The height of the pointers represents the level of abstraction of each processing level. Processing is going on in parallel but the model is linear in the sense that lower levels cannot be processed when the pointer of the higher level has not reached the current point in time. The density of arrows pointing upwards indicate the level of detail of motor preparation and feedback control.



A further assumption of the model is that the information load for a higher level of the model affects performance time (and other performance characteristics) of that part of the written trace for which real time production coincided with actual preparation of that higher level. For example, if the retrieval of a word would be thought to be realized during the real time production of the immediate preceding word, increase of the retrieval load necessarily would lead to prolongation of writing time for that preceding word, but not for any other part of the writing trace.

The main strategy of the research reported here has been to construct natural, cursive handwriting tasks — in our experiment writing words upon visual dictation — which were varied according to different processing levels.

1. Word Level. At the word level we varied word length and phonemic similarity. It is hypothesized that graphemes are selected at word level, i.e., word by word. Longer words probably lead to heavier processing demands than shorter ones (Sternberg, et al., 1978). Word length has been varied by dictating words of either three or five letters (consonant/vocal/consonant sequences or vocal/consonant/vocal sequences, e.g., 'feb,' 'efu,' 'febeb,' 'efufu'). These words have no specific meaning in Dutch. During the grapheme selection process words are supposedly stored in a short term store, probably in a phonemic code (Ellis, 1982; Van Nes, 1985). We tested the hypothesis that phonemically dissimilar words (e.g., 'efafu') cause heavier processing demands than words that repeat their phonological structure (e.g., 'efafa').

2. Letter Level. At the letter level we investigated the effects on processing demands of two structurally resembling letter forms ('l' and 'b'), differing only in their length. We hypothesized that, in analogy to Klapp (1976), the letter with the longer trajectory would lead to heavier demands upon the preceding context.

3. Letter Connection Level. Finally, at the level of real time stroke production, we varied the connecting strokes between successive letters bringing about a continuation of an ongoing rotational direction, e.g., anti-clockwise rotation of the last stroke of a cursive 'f' connected with an anti-clockwise first stroke of a cursive 'e,' or an alternation of an ongoing rotational direction, e.g., the transition of a clockwise rotating last stroke of a 'g,' connected with an anti-clockwise turning cursive 'u.'

In general terms our model predicts that (a) variations of the information load at the word level, the graphemic level and the letter connection level have their own specific boundaries in the writing trace between which load effects should be found; and that (b) the processing on higher levels precede the processing on lower levels, i.e., that effects of the difficulty of letter connections never manifest themselves earlier in the writing product than the effects of letter and word complexity and that effects of letter complexity in their turn do not show themselves before effects of word complexity.

Measuring Processing Demands

Most studies on human performance have used chronometric analysis of the effects of task variables upon performance. Many studies concentrated upon reaction time, i.e., the time needed to start a speeded reaction. Some of these studies analysed ongoing performance but then, in most instances, only movement duration was studied. In the present study we added the analysis of the dynamic characteristics mean and peak velocity to the study of latency and movement time. For each experimental condition we determined the latency to start writing, and for the first, second and third letter separately the following measures: a. duration, b. length, c. mean velocity, d. peak velocity.

We cut the chronometric structure into successive parts, labelled latency, letter 1, letter 2, letter 3. The reason for this was that if processing demands from one or a combination of the levels that we varied would be reflected in the latency and/or performance data, the extent to which those effects appear earlier in the sequential parts of the task preceding the upcoming demand, would be an indication of how far ahead processing for that particular level is initiated.

In our experiment we varied processing demands at the letter level and the letter connection level by using different letters at the third letter position. Extrapolating from earlier research (Teulings, Thomassen & Van Galen, 1983) in which evidence was brought up that programming for specific letter forms is started one letter position earlier than the real time execution, the second letter of the experimental words was analysed in more detail. We therefore cut the recorded movement trajectory into successive segments by means of a computer aided procedure. For more details see under 'Analysis.'

METHOD

Subjects

Fifteen adult, right-handed subjects, students and staff members, served in the experiment. They were selected from a larger pool on the criterion that they were accustomed to write cursively and with allographic letter forms which satisfied the presuppositions about sequence length and directional rotation we had used when constructing our list of experimental words.

Materials

To study the effects of these classes of processing demands upon the performance of handwriting we devised a list of artificial words consisting of 36 different words, 12 with a length of three letters and 24 consisting of five letters.

The longer words consisted of a group of phonemically similar and an equal group of phonemically dissimilar words. Phonemic similarity was defined as a repetition of the last two consonant/vocal combinations of the five letter words (e.g., 'efufu;' 'efafa;' 'felel,' 'febeb'). Phonemic dissimilar words were constructed through substitution of either one of the vocals of the last two consonant/vocal pairs of a similar word by a phonologically different letter (e.g., 'efufa;' 'efafu') or the change of one of the consonants (e.g., 'feleb;' 'febel').

The effects of the length of separate letters was studied by a systematic variation of the number of strokes of the letter at the third position within words. As a short letter the 'l' and as a longer letter the 'b' was chosen. A subset of two out of 12 short words and four out of 12 long words had a letter 'l' at the third letter position and two, resp. four had a 'b' as the third letter (see Table 1, uppermost panels).

The type of letter connection (continuation of direction of rotation, like in going from 'l' to 'u' versus alternation of direction of rotation, like in the connection of 'j' to 'u'), was investigated by constructing words that had at the third letter position either a letter that enabled a continuation of the direction of rotation of the end stroke of the immediately preceding letter or made necessary an alternation of rotation. The middle panels of Table 1 give a listing of two short and four long words in which an anti-clockwise rotation is continued, and two, resp. four words in which anti-clockwise rotation changes into clockwise. The lower panels contain words in which a clockwise rotation of the endstroke of the second letter is continued or changed at the begin stroke of the third letter.

One of assumptions of our model about the extent and the time boundaries of the effects of processing demands of oncoming parts of the task upon performance characteristics of the ongoing element of the task was that heavier conditions for ongoing elements enhance the probability of performance decrements caused by advance programming of oncoming elements. Because we were especially interested in the effects of conditions which influence the third letter and because we expected possible effects to become visible in the performance of the second letter we also varied the motoric complexity of these second letters. We shall call these letters reference letters. Within the list of words we had, for each comparison of conditions, words with a short reference letter ('e,''l,''j') and words with a long second letter ('u,''f,''g'). The full list of words used in the dictation task has been listed in Table 1. Each of the short words was replicated twelve times and each of the long words six times. The replications were dispersed randomly over 288 experimental (plus 3 warming up) trials. Because there were 12 different short words and 24 different long words the total number of 3 letter tasks was equal to the number of 5 letter tasks.

Table 1 Listing of 36 writing tasks. The uppermost panels were used to test the effects of word length, phonemic similarity and length of the third (context) letter upon latencies and performance measures of the first two letters. Middle and lower panels are devised to investigate effects of wordlength, phonemic similarity and letter connections.

	Word length			
	short	long	short	long
	e ←	reference letter	→ u	
context letter: l	fel	felel / feleb	ful	fulul / fulub
context letter: b	feb	febeb / febel	fub	fubul / fubub
	l ←	reference letter	→ f	
context letter: u	elu	elulu / elula	efu	efufu / efufa
context letter: a	ela	elala / elalu	efa	efafa / efafu
	j ←	reference letter	→ g	
context letter: u	eju	ejuju / ejuja	egu	egugu / eguga
context letter: a	eja	ejaja / ejaju	ega	egaga / egagu

PROCEDURE

The experiment consisted of the cursive production of 288 words with a ballpoint, connected to a computer (PDP 11/45) on a normal sheet of paper that was placed on the X-Y digitizer. The computer monitored the presentation of the stimulus words on a Vector General Display (exposure time 1.5 s.), the production of a starting signal (low tone, 10 ms. after an interval of 0.5 s. after the visual presentation of the word had ended), sampling X- and Y-values of the pen position with a frequency of 100 Hz during

2.0 s. (short words) and 3.5 s. (long words) and the production of a high tone (10 ms.) meaning that the recording interval had ended. The subject was instructed to read at the beginning of each trial the stimulus word from the screen, to direct his/her attention to pen and paper and to start writing after the low tone had sounded. After the high tone the subject should again fixate the screen on which after an interval of 1.0 s., the next word was presented. The task was introduced as a natural handwriting task. Neither speed nor accuracy was stressed. The subject was asked to write in his usual style and neatness. Before the experimental series started the subject performed 35 training trials. The experimental series of 288 trials was interrupted for a few minutes every 35 trials to rearrange the writing sheet and to prevent work overload of the subject. The subject's arm and hand rested on a constant position on the tablet. After each trial the subject moved up the writing sheet with his left hand and placed his right hand back to the starting position in such a way that the next word could be written with the same state of the musculature of arm, wrist and hand as during the preceding trial.

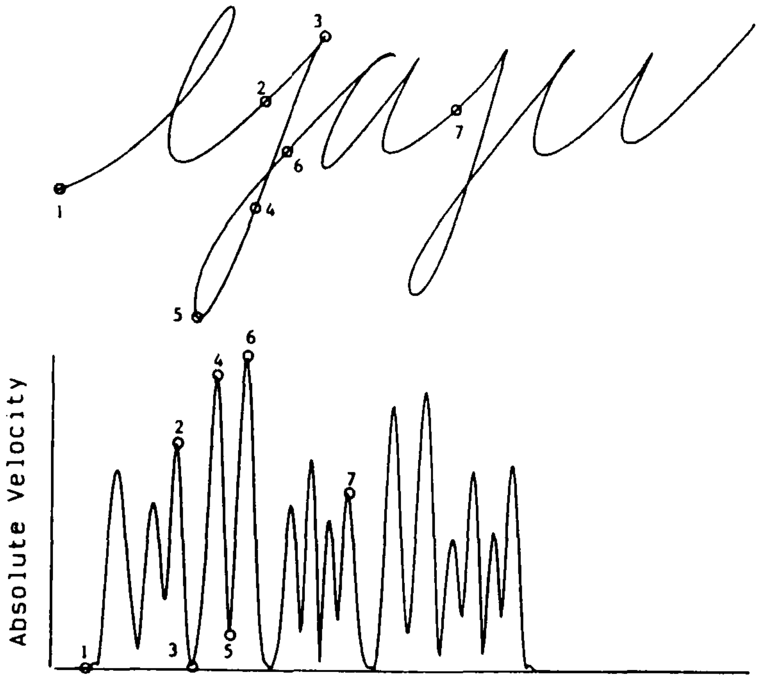
Analysis

Each trial was recorded with a sampling frequency of 100 Hz. The absolute velocity pattern of each trial was used to determine, with the aid of a maximum/minimum searching program, data subsets for latency, i.e., the time between presentation of the starting tone and the beginning of the first stroke, the first letter, the successive segments of the second letter and the third letter. Transition points between letter segments were defined as those points of the connecting strokes between letters where the absolute velocity reached its maximum. Within the second letter performance measures of successive segments were determined. Segments were defined as successive parts of the written trajectory, lying between points of maximum and minimum velocity. The boundaries of these segments and the points of transition between letters were used to divide each record of a word into different parts:

(a) The RT, i.e., the latency between onset of the starting tone and first movement of the pen.
(b) The trajectory of the first letter.
(c) The trajectory of the second letter.
(d) The trajectory of the second letter minus the last segment. The rationale to determine the data of the second letter without its connecting stroke to the third letter is that we wish to study effects of processing demands from context letters as much as possible independently from the physical interactions of connecting strokes.
(e) The trajectory of the last two segments of the second letter before the connecting stroke to the third letter. We reasoned that possible local effects of programming oncoming letters would be visible in the last context free stroke of the preceding letter.
(f) The trajectory of the third letter.
(g) The trajectory of the first and second letter together.

The cutting procedure is illustrated in Figure 2. For each of these movement trajectories the computer measured the duration, the length, the mean velocity and the peak velocity.

Figure 2 Cutting procedure to define successive segments of the velocity pattern of a writing task. Numbers in velocity pattern correspond to the numbers within the writing trace.



For data of correct trials only, and for each subject the medians over replications for each word were computed. These values were entered into files for the analysis of variance according to the designs needed for the analysis of the effects of the different independent variables.

RESULTS

Effects at Word Level: Phonemic Similarity and Word Length

Phonemic similarity was analysed by means of a 15 (subjects) * 6 (reference letters) * 2 (context letters) * 2 (phonemic similarity) design for analysis of variance on the RT and movement data of only the long words (phonemic similarity was not varied within short words). There was a small but nonsignificant effect of the phonological structure of words on RT. Phonologically dissimilar words were initiated 9 ms. later than phonologically similar words (302 versus 293 ms.; ($F(1,14)=1.95$; $p=0.18$). Nor was any other factor significant for the RT-data. The movement data show quite intriguing interactions between phomenic similarity and the identity of the reference letters (the letters at the second position) upon the mean velocities of letter 2 and letter 3 resp., and the maximum velocity of letter 2. It turns out that phonemic similarity speeds up the writing process for the second and third letter of words with the reference letters 'e,' 'u' and 'l' and inhibits the writing speed of these letters of words with reference letters 'f,' 'j' and 'g.' No further effects of phonemic similarity were found.

Word length effects were tested by means of analysis of variance upon the full dataset with a 15 (subjects) * 6 (reference letters: 'e,''u,''l,''f,''j,''g') * 2 (classes of context letters: 'l' and 'u' versus 'b' and 'a') * 2 (word lengths: three-versus five-letter words). The factor phonemic similarity was confounded because no main effects for this factor had been found. We shall report on significant findings only for RT and movement data.

The mean latency for long words was 298 ms. and for short words 286 ms. The difference of 12 ms. for words with one syllable more may be considered to be a significant finding ($F(1,14)=4.15$, $p<0.06$). It should be remembered that these data have been collected without time pressure. Subjects started writing at a convenient interval after the starting signal had sounded. Although the variance of the latency has undoubtedly been increased by this procedure we find a difference between words differing one syllable in length which is very near to the value of 10 ms. for one extra syllable in speech tasks as reported by Sternberg, et al. (1978). We found no significant interactions between word length and any other of the variables. Figure 3 illustrates the effects of word length on RT for the successive reference letters. The data on the movement characteristics mirror those on RT. The longer words are started with a significantly higher peak velocity for the first letter (8.649 cm/s vs. 8.542 cm/s; $F(1,14)=8.58$; $p<0.05$). In the third letter the length effect is even more pregnant. The short words then only reach a peak velocity of 7.700 cm/s whereas the long words peak to 8.244 cm/sec ($F(1,14)=20.02$; $p<0.001$). Probably, with short words the stop at the end of the third letter slows down the writing movements. The mean velocity data show a comparable picture. Whereas the mean velocity for the first letter in the short words does not differ from the mean velocity of the same letters in long words, during the production of letter 2, and furthermore in letter 3, the picture was reversed. Now the pen has arrived at a higher mean velocity with long words (letter 2: $F(1,14)=7.72$; $p<0.05$ and letter 3: $F(1,14)=5.25$; $p<0.05$). Figure 4 depicts the chronometric development of RT and mean velocity in short and long words. As the figure suggests we may notice a trade-off between the RT-and the movement data. Longer words lead to longer latencies to start writing. But, once started the subject speeds up his performance perhaps to compensate for the longer latency and the longer overall duration of the task.

Figure 3 Reaction time for short (open) and long words (shaded) for each of the reference letters.

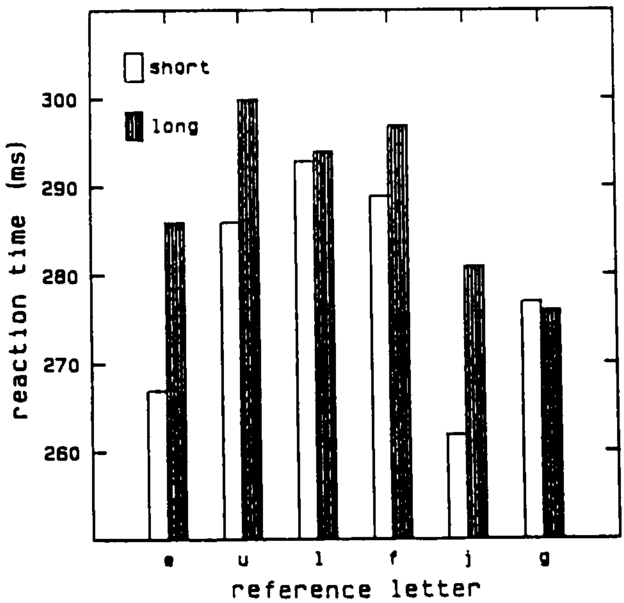
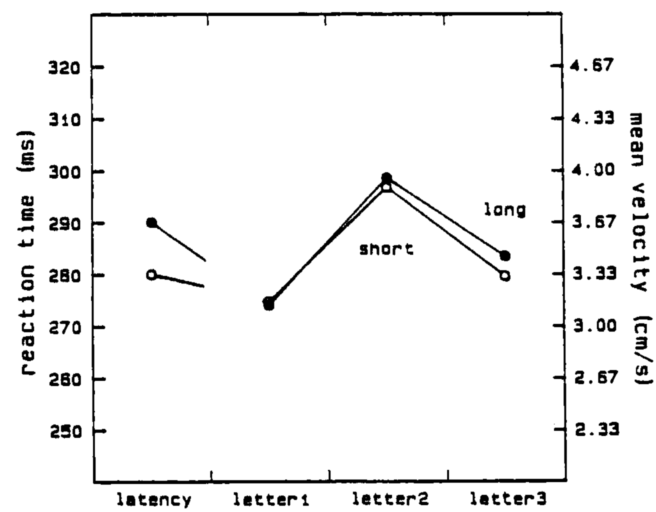


Figure 4 RT and mean velocities of first, second and third letter as a function of word length. Long words (closed circles) are initiated later than short words (open circles), but they are speeded up once the writer starts moving.



Effects of the Length of Letters: l Versus b

Length of letters was varied through extending the number of strokes within a letter, without at the same time changing the initial strokes of the letter. Good candidates are 'l' and 'b.' We tested the effects of 'l' and 'b' with the words of the upper panels of Table 1 by means of a 15 (subjects) * 2 (reference letters: 'e' and 'u') * 2 (context letters: 'l' and 'b') * 2 (wordlengths: three-and five letter words). The effect of 'l' versus 'b' has been found at two levels before the 'l' or 'b' is written. Firstly, there is a significant prolongation of the movement time of the immediately preceding letter: mean duration for 'e' and 'u' (without last segment), preceding 'l,' is 270 ms. and preceding 'b' 273 msec. ($F(1,14)=5.18$; $p<0.05$). The difference is small but statistically reliable. The difference is mainly localised within the last two segments of the body of the reference letter: this measure is 99 ms. before an 'l' and 101 ms. before a 'b.' The difference is reliable ($F(1,14)=5.18$; $p<0.05$). At a more remote distance, namely in the data of the first letter we found an effect of 'l' versus 'b' upon the length and a trend towards significance for the maximum velocity. For the context letter 'l' the 'f' is written larger (2.661 cm. versus 2.623 cm.; $F(1,14)=6.03$; $p<0.05$) and its peak velocity tends to be higher. For the duration of 'b' and 'l' themselves we found an interaction with the length of the reference letter. The duration of 'b' after an 'e' is longer than after an 'l.' It could be that the longer duration of 'u' permits more parallel preparation of the oncoming 'b.' RTs were not different, apart from a significant effect of wordlength ($F(1,14)=4.99$; $p<0.05$). It seems that longer letters give rise to heavier processing demands during the two preceding letters. Most of the effect, however, is concentrated upon the immediately preceding letter.

Effects of Letter Connections: Alternation Versus Continuation of Rotation

For analysis of effects at the level of strokes connecting letters to each other the words of the middle two and lower two panels of Table 1 are relevant. We analysed the 'l' and 'f' words (middle panels) and the 'j' and 'g' data separately. Words with reference letters 'l' or 'f' connect to the context letter ('u'/'a') with an anti-clockwise turning endstroke. The block of data concerns connections from a clockwise turning pen position.

Because connecting strokes are probably most sensitive to the immediate context, we first searched for effects of alternation and continuation upon the immediate preceding letters. These are the reference letters 'l' and 'f' for the dataset we will report on firstly. Alternation of turning direction versus continuation had a significant effect upon the peak velocity data. The maximum velocity for the reference letter, as well as for this letter minus the last segment was significantly higher for words with alternating connecting strokes (11.075 cm/s versus 10.712 cm/s; $F(1,14)=6.66$; $p<0.05$). We also found changes of the trajectory leading to the oncoming turning change. The length of the body of the reference letter was shorter when the direction of rotation was continued. For both letters 'l' and 'f' a picture emerges of greater difficulty for continuation of the same direction of rotation.

A quite different picture shows up when we consider the 'j,' 'g' data. Now the duration of the second letter is longer for words which alternate direction of rotation. This is especially true for the reference letter considered without the connecting stroke: the movement time for the second letter minus last segment is 397 ms. before continuation and 405 ms. before alternation ($F(1,11)=5.61$; $p<0.05$). The mean velocity of the second letter is 4.017 cm/s vs. 3.949 cm/s before continuation and alternation conditions respectively. For 'j' and 'g' the data consistently show a different picture than for 'l' and 'f.' For 'j' and 'g' alternation of the direction of rotation is the more difficult condition.

Change of direction of rotation had no significant effects upon more distant trajectories of the writing task. Only for the 'l' and 'f'-data there was a tendency for shorter latencies for words with an alternation of turning direction (285 vs. 303 ms., $F(1,14)=4.42$; $p=0.0516$). So far, it might be clear that stroking vectors really do have effects upon the ongoing motoric processes. These effects are not only biomechanical — localised in the stroke in which the change of rotation takes place — although we did find changes in the third letter. In general, the more difficult condition, which is continuation for 'l' and 'f' and alternation for 'j' and 'g,' enlarges the trajectory of change. But, more important for our search for a model of the dissipation of resources over the time course of preparation and real time execution, changes of stroking vectors are foreshadowed in the immediately preceding trajectories of a letter.

DISCUSSION

The main objective of our study has been to trace the time boundaries of processing of motoric demands at different levels of the handwriting process. For this reason we developed a quasi-natural handwriting task in which motoric demands on word-, letter-and stroke level were manipulated. Our strategy has been to measure precisely latencies and movement characteristics and to relate these values to the dimensions we used for the construction of the tasks. It came out that at the word level word length had a consistent effect upon latency and movement dynamics. The relation, however, was reversed for latencies and velocities. Long words took longer to start but were speeded up after the first letter. We probably have to do with a strategic effect which is contrary to the more often reported effect of heavier retrieval load for longer words (Sternberg, et al. 1978). Our findings and interpretations do not mean that retrieval demands are not present. In a different study (Van Galen & Van der Plaats, 1984) we could show that within words the time to produce similar letters is dependent upon the position within the word. It was found that earlier letters were written slower and we interpreted this finding as evidence for the retrieval load hypothesis.

In the present study we found no consistent effects of phonemic similarity upon RT. It could be that with visual presentation of the stimuli the processing demands of encoding and reading phonemically similar and nonsimilar words are too easy to cause an effect upon motor preparation. Research with more difficult tasks may bring up a more final conclusion.

Letter length consistently influenced the preceding letters. The outcome corroborates earlier findings by Teulings, Thomassen and Van Galen (1983) that preparation of the motoric structure of letters is realised one or two letters in advance.

The curvature of individual strokes, finally, seems to be prepared only two or three agonist/antagonist bursts in advance. An oncoming change of direction of rotation with 'l' and 'f' facilitated writing, whereas it was the more difficult condition for the context letters 'j' and 'g.' One possible explanation could be that different anatomical structures are engaged in the realisation of change of rotation. For 'l' and 'f' it is the more distal, finger system which takes over when the pen alternates from an anti-clockwise to a clockwise rotation. For the finger system this is not a particular difficult task, on the contrary, the motor system may profit from an alternation from anti-clockwise to clockwise because clockwise segments are probably more easily recognized within the predominant set of anti-clockwise strokes in the motor buffer. For 'j' and 'g' alternation is much more difficult. Their endstrokes come from far below the base line and ask for the more difficult coarticulation of wrist extensions with finger movements for the onset of the letter 'u.'

Although we did not compare the form of 'u' and 'a' in continuating and changing contexts it is certainly true that form changes could be an important source of information to check chronometric explorations. In the transition from a 'g' to 'u' we often observed a deformation of the sharp initial upstroke of the 'u' into a more curved trajectory resembling that of the initial stroke of a letter 'a.' In natural handwriting it is the linguistic and semantic context which enables the reader to correctly identify even deformed letters.

Many of the data mentioned so far are consistent with the predictions derived from our mixed linear and parallel model of handwriting. From the two word level factors (phonemic similarity and word length) word length had a performance effect that goes back to the latency period immediately preceding the word. From this finding in our quasi-natural experimental writing task it can be concluded that the preparation load of words is foreshadowed at least in the interval between successive words. Letter complexity effects act on a narrower time scale. They work only upon immediately preceding letters. The outcome is consistent with the view that grapheme selection, as a hierarchically lower process, follows word retrieval, and therefore, according to the mixed model, letter complexity has effects with narrower time boundaries than word complexity. Letter connection effects expressed themselves also in particular segments of the writing trace as did the other level effects. It was the immediate context stroke that reflected connection difficulty. The pointer in the model (Figure 1) reflecting the time border of the preparation of specific strokes is not more than one or two strokes ahead. For both predictions stated in the introduction — the existence of level specific time boundaries and the precedence of higher levels over lower levels — the data are highly supportive. Some caution, however, is necessary. It is difficult to say whether applicability of the model may be claimed for different motor tasks and for handwriting under different conditions. In natural tasks the dicrepancy in time between real time execution and mental preparation of specific parts of a task may vary greatly. In formulating a difficult text the ideas of the writer may fly far ahead of the tardy word finding and motoric production processes. But in essence, the model outlined in Figure 1 does allow for such variations of human skill.

The presented model of handwriting has a linear as well as a parallel structure. Although in much of the recent literature (Broadbent, 1984) the linear concept seems to be the counterpart of the parallel concept we have tried to give room to both concepts. Parallel processing is proposed to be the true description when the action plan and its real time development is considered as a whole. A linear structure is assumed when we concentrate upon the order of processing of one single unit of the action plan. In the latter case higher processing levels are thought to precede lower processing levels. Many of the current models of psychomotor tasks are either strictly hierarchical or strictly parallel in nature (Van Galen & Wing, 1984). In the field of typing Norman and Rumelhart (1983) proposed an activation-triggered schema system that resembles in some respects our handwriting model. In their model parallel as well as serial preparation of key strokes takes place. The difference, however, with our handwriting model is that we make predictions about the real time execution at a more detailed level. Of course, the possibility for making these predictions is given by the relative slow real time execution of handwriting combined with the very precise and fast sampling techniques of movement dynamics.

The study of motor behaviour may profit from detailed analysis of handwriting tasks. Linear versus parallel processing is an enduring problem in the search for information processing models of human behaviour (Posner & McLeod, 1982) and an exact delineation of the time boundaries of processing demands may contribute to more satisfying theories. We feel that the present study may contribute to the view that processing on different levels is done in parallel but not without interfering or facilitating real time movement execution. The individual effects of task levels are relatively small. Motor execution in handwriting is done at a fairly constant manner. The standard deviations of strokes for individual subject produced in different contexts are extremely low. Therefore it is possible to find tiny but consistent and theoretically important effects. More research along these lines is possible and needed.

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Graphonomics: Contemporary Research in Handwriting
H.S.R. Kao, G.P. van Galen, R. Hoosain (eds.)

THE ELEMENTARY UNITS OF PROGRAMMING IN HANDWRITING

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INTRODUCTION

The identification of a production unit in motor programming has been posited by Sternberg, Knoll, Monsell and Wright (1983) to be a stress-group in speech sequences and a single keystroke in typing sequences. The idea of the existence of a production unit is based on the systematic and consistent way in which reaction time (RT) and movement time (duration) in a simple-reaction time paradigm vary as a function of the number of units contained in a movement sequence. In their subprogram-retrieval model, both RT and average duration per unit increase approximately 7 msec. for each unit in the sequence. In speech and typing, the RT and element duration effects seem to provide evidence for the identity of the production units; the slope is not affected when the stress groups contain additional unstressed words or syllables.

Since speech and typing research has demonstrated some success in inferring production units, scientists have begun to search for the elementary units that may comprise the motor program for handwriting. Handwriting is a well-learned skill which is easily decomposed into smaller movement units so that it should be possible to identify its component parts. In the past seven years, several efforts have been made to separate these components along somewhat natural partitions such as letters, or constituent strokes of a letter.

Teulings, Thomassen, and Van Galen (1983) attempted to discover the identity of a unit in handwriting by investigating whether it was a letter or a stroke. In this experiment, subjects wrote pairs of cursive letters in choice reaction time, partially precued reaction time, and simple reaction time conditions. The letter pairs contained either repetitions or alterations of identical units, defined in terms of letters and/or letter strokes. It was found that reaction time was affected by the number of letters and not by the number of strokes, and this suggested that an elementary unit of handwriting is a letter.

Using a different type of methodology, Stelmach and Teulings (1983) examined the advance planning in letter sequences, and concluded that most of the programming benefits observed in the execution of letter strings are localized in the first letter stroke with further "on-line" programming occurring during the execution of the remaining letters.

Hulstijn and Van Galen (1983) argued that since handwriting is learned and practiced as letters, and is typically executed at relatively slow movement rates, letters may be the basic production unit. While their data on the execution of strings of letters did show a small linear increase in RT with sequence length, they did not find, however, that the time to write a letter increased with sequence length. These findings could be interpreted as partial support for the subprogram-retrieval model, but Hulstijn and Van Galen (1983) preferred to explain their data by proposing a parallel processing model in which only the first unit is completely programmed with succeeding elements programmed during execution. The time needed to write an arbitrary letter, like an *a*, takes approximately 300-400 msec., which is very long compared to the time needed to pronounce one stress group (e.g., 100 to 200 msec.). The low maximum output rate of handwriting as compared to speech is probably due to the fact that the handwriting movements are produced by a limited number of antagonistic muscle systems, each having their physiological frequency-band limits, whereas in speech, many muscle systems are coarticulating in parallel. Indeed, the frequency spectrum of handwriting movements appears to decrease rapidly beyond 5 Hz (Teulings & Maarse, 1984). Thus, in normal writing, there is probably no need to preprogram even the fastest handwriting sequence, since "on-line" programming may be possible during movement execution. So in order to find any sequence-length effects, movement units of shorter durations should be investigated.

Few attempts have been made to examine handwriting in situations conducive to speeded execution: Wing (1978) performed an experiment in which he examined the reaction times for letters (V, N, W, and M) and was interested in whether reaction time increased with the increasing number of vertical strokes. He found only the letter V was faster than the other letters, and he concluded that the data did not support the notion of increased preparation time with increasing number of strokes. Inspection of Wing's data does reveal, however, that one of the two subjects did show some trend in the predicted direction. Further, up-and-down stroke pairs had positively correlated durations, suggesting that the elementary unit may be as small as one stroke pair. In Stelmach, Mullins and Teulings (1984), it has also been concluded that RT and mean duration per stroke are not in accordance with Sternberg, et al. (1983), but this conclusion might appear premature because the stroke lengths have not been controlled. Therefore, two of those experiments are reported here as Experiments 1 and 2 but now include stroke lengths and some noteworthy correlations.

Despite the efforts of those who have examined the various hypothesized production units of the motor program for handwriting [e.g., sinusoid swing around the equilibrium point (Hollerbach, 1981), metronomic process (Wing, 1978), and letter (Hulstijn and Van Galen, 1983)], there are no handwriting data yet available that clearly show programming effects on both RT and average duration per unit as predicted by the subprogram-retrieval model of Sternberg, et al. (1983). The purpose of the present series of experiments is to attempt to create conditions such that the effects upon RT and duration per unit may be observed in simple handwriting tasks. In order to encourage motor programming, well-trained subjects were required to perform simple handwriting sequences in a very short time. The writing sequences chosen were patterns of repetitive up-and-down strokes with the hope that these short units may form production units of a motor program.

EXPERIMENT 1

Subjects

Subjects were two right-handed male and two right-handed female psychology students.

Apparatus

The writing movements were recorded by means of a computer controlled digitizer (Vector General Data Tablet DT1) placed in front of the subject and aligned parallel to the subject's horizontal writing line. The position of the pen tip, expressed in horizontal and vertical coordinates was sampled at a rate of 200 Hz with a combined RMS error better than 0.2 mm. The pen tip was an ordinary ballpoint refill and the subject wrote on a sheet of nonlined paper fixed on the digitizer surface. The visual stimuli were presented by means of a refresh display (Vector General Graphics Display Series 3 Model 2D3). Computer-generated acoustical stimuli were presented through a loudspeaker.

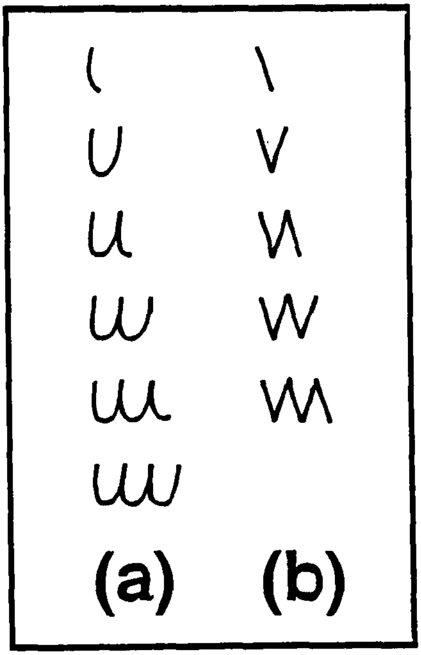
Writing Patterns

The writing patterns consisted of 1 to 6 strokes of a repetitive figure resembling the cursive letter *u* (See Figure 1a).

Procedure

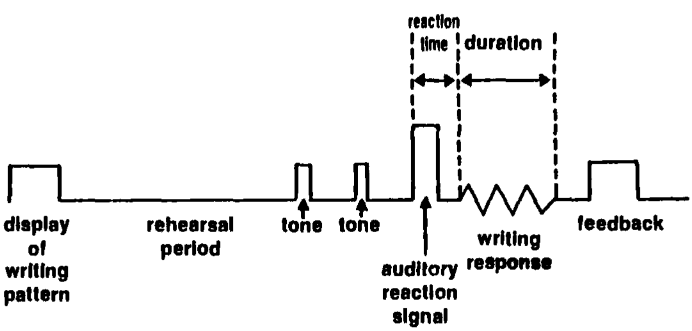
A typical trial proceeded as follows (see Figure 2). First, a writing pattern was presented on the display screen for 500 msec. followed by a 2500 msec.

Figure 1 The writing patterns used in Experiments 1 (a), 2 (b), respectively.



rehearsal period, which the subjects were encouraged to use to prepare their response. Then, two 10 msec. warning beeps of 1 kHz occurred, 500 msec. apart. After another 500 msec., a 100 msec. high frequency beep (2 kHz) was presented as the "go" signal, and all pen movements during the following 1000 msec. were recorded. To prevent the subjects from anticipating, in 20% of the trials the "go" signal did not occur (catch trials). Feedback information on the number of trials completed and on the total movement time was presented 400 msec. after the recording period. After a 500 msec. delay, the next trial began automatically.

Figure 2 Timing schedule of events in a typical trial.



Each subject completed 9 blocks of 90 trials in 2 one-hour sessions on different days. The first 5 blocks were practice, only the last 4 blocks were entered into the analysis. Each block consisted of 12 repetitions of every writing pattern, plus 18 catch trials, all presented in random order. At the end of each block, the subject received a score based on time and number of catch errors, to encourage speed and accuracy.

The writing movements were lowpass filtered (transition band was 16 to 48 Hz; see Teulings & Maarse, 1984) and were automatically analyzed (strokes were localized by detecting zero crossings of the vertical velocity component) in terms of RT, duration per stroke, and length of each stroke (i.e., linear distance between the low point and the high point of the stroke). Medians and intercorrelations over the 12 repetitions of RT, stroke duration and stroke length per writing pattern per block were determined for each subject. These data were entered in a 4 subjects × 4 blocks × 6 patterns analysis of variance.

Results and Discussion

As seen in Figure 3, the average RT as a function of the number of strokes does not show a significantly linear ($F(1,9)=2.48$, $p>.1$) increase even if we would restrict the analysis to 3-, 4-, 5-, and 6-stroke patterns in order to satisfy the element-invariance requirement of differences in the elements themselves, as discussed by Sternberg, Monsell, Knoll and Wright (1978). The vertical bars indicate the standard deviations of the means over blocks and over subjects.

Inspection of the length per stroke reveals that the subjects produced writing strokes of different lengths for each pattern and for each serial position (see Figure 4). Indeed, according to Duncan's multiple-range test at the 0.05 level, the lengths of the strokes form various homogeneous groupings getting progressively shorter. (Since subjects were instructed to minimize total movement time, they may not have been able to reproduce lengths of the strokes accurately as well). Mean RT and mean length of the first stroke appear to be highly correlated (Kendall's $r=.83$, $p<.02$); therefore, it could be the case that varying stroke lengths might have obscured the RT effect.

Figure 3 Average RT as a function of the number of strokes in Experiment 1. Vertical bars represent the standard deviations of the means.

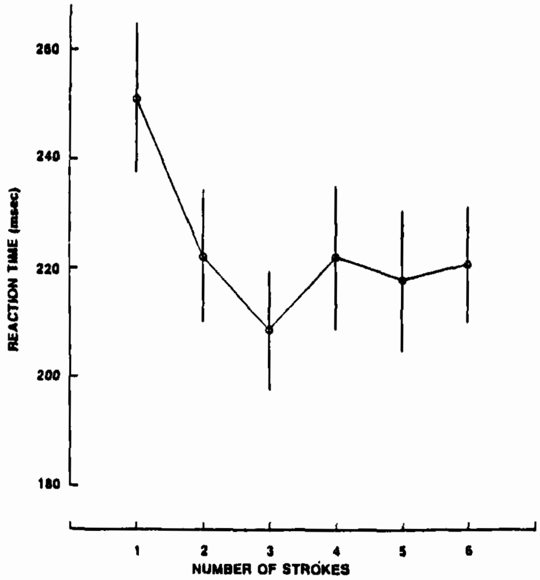
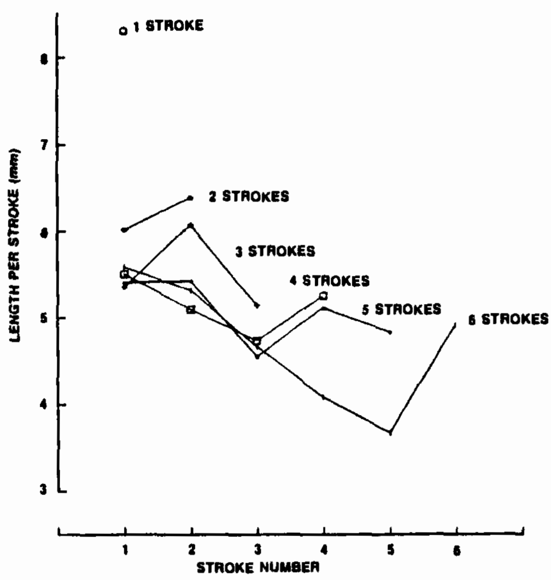


Figure 4 Average length per stroke for each of the patterns in Experiment 1.



The correlational analysis further revealed that durations of non-adjacent stroke pairs tended to be positively correlated (sign test, $N=10$ patterns × non-adjacent stroke pairs, $x=9$, $p<.05$), which might be explained by assuming a time-scale factor common to all strokes within each individual writing pattern (Viviani & Terzuolo, 1980; see, however, Gentner, 1982). As a rule, adjacent strokes should be negatively correlated due to either the inaccuracy of the estimate of the time point between them, or the temporal noise in the stroke duration (see Wing, 1980; Wing & Kristofferson, 1973). Therefore, it is remarkable that the durations of strokes 1 and 2 in the 4-, 5- and 6-stroke patterns did not show negative correlations (in the 5-stroke pattern, the mean of the correlation coefficients was even significantly positive: $r=.14$, sign test, $N=16$, $x<4$, $p<.05$). Confirming our expectations, the durations of strokes 2 and 3 tend to be negatively correlated (in the 6-stroke pattern even significantly negative: mean $r=-.19$, sign test, $N=16$, $x<4$, $p<.05$). This systematic alternation of positive and negative correlations suggests a handwriting unit consisting of a down-and-up stroke, or a complete guirland which may still be a too much time consuming unit. It should be noted that the grouping of strokes differs from Wing's data (which was up-and-down) but we suggest that this is a consequence of the choice of guirlands instead of zig-zags.

In order to facilitate a more distinct delineation of up and down strokes that also might allow for better control of the length per stroke, another experiment was conducted with the same subjects using a straight-line writing pattern instead of a curve.

EXPERIMENT 2

In this experiment, we used handwriting patterns consisting of 1 to 5 (instead of 6) strokes of a repetitive straight-line zig-zag resembling the letter V (see Figure 1b). Except for this change in writing pattern and an increase in the number of trials analyzed to 75, 15 of which were catch trials, this experiment was analogous to Experiment 1. Also, the same subjects participated as in Experiment 1.

Results and Discussion

Apart from the divergent RTs for the 1and the 2-stroke pattern, RT now shows a significantly linear increase from 3to 5-stroke patterns ($F(1,6)=7.59$, $p<.05$) of 5 msec. per additional stroke (see Figure 5). However, this increase is not accompanied by an increase in the average duration per stroke (i.e., 129, 114, 117 msec. for 3-, 4-, and 5-stroke patterns, respectively). Furthermore, as in the previous experiment, the lengths of the strokes were still not homogeneous (Duncan's multiple-range test at 0.05 level yielded several (5) groups of length data) (see Figure 6).

Figure 5 Average RT as a function of the number of strokes in Experiment 2. Vertical bars represent the standard deviations of the means.

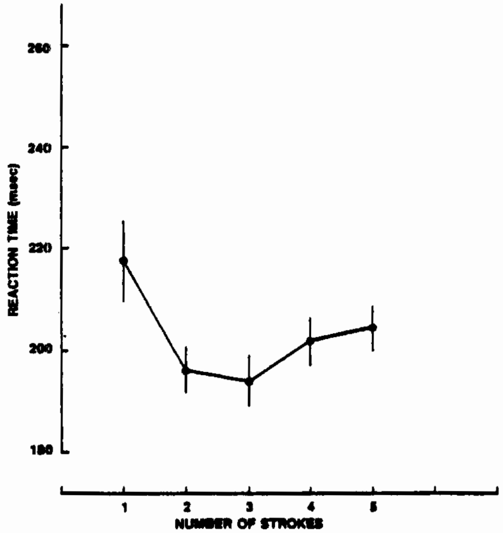
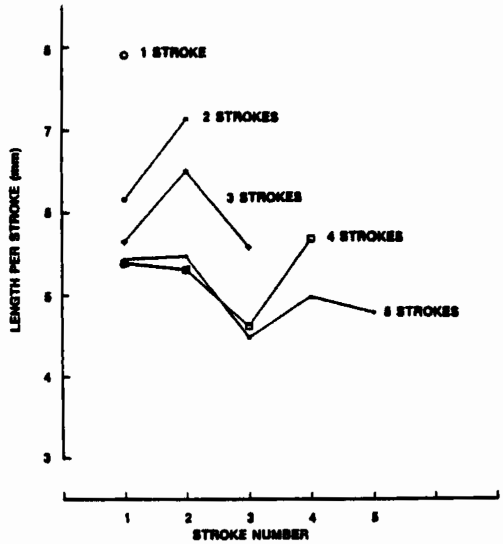


Figure 6 Average length per stroke for each of the patterns in Experiment 2.



The correlational analysis revealed that this zig-zag writing pattern may be more likely to be treated as a series of separate strokes. This can be seen in the 4 and 5-stroke patterns, where the durations of 6 out of 7 adjacent stroke pairs tend to have negative mean correlations, which was argued in Experiment 1 to be the rule (the correlation between stroke 1 and 2 in the 5-stroke pattern is even significantly negative: mean $r=-.29$, sign test, $N=16$, $x<4$, $p<.05$). Non-adjacent stroke pairs still show their tendency to be positively correlated, as in Experiment 1 (sign test, $N=10$, non-adjacent pairs, $x=1$, $p<.02$). So, although stroke lengths are still not homogeneous, we found evidence for the stroke being separate units.

Using this information on straight-line writing patterns appearing to be separated into distinct strokes, a third experiment was conducted employing even a more simple straight-line writing pattern than the last experiment, in order to en the last experiment, in order to enable the subjects to have sufficient control of the length of the strokes.

EXPERIMENT 3

In this experiment, another aspect of the writing pattern was eliminated: the horizontal progression. This meant that the subjects simply made the required stroke without lateral movement, i.e., each stroke was executed on top of the other. The handwriting patterns consisted of 1 to 5 separate up- and down-strokes. In all other respects, this experiment was analogous to Experiments 1 and 2. The same subjects participated as in Experiments 1 and 2.

Results and Discussion

First, consider the length per stroke for all patterns. It can be seen that the subjects met quite well the implicit requirement to make all strokes equally long. Indeed, according to Duncan's multiple-range test at the 0.05 level, all stroke lengths did form one homogeneous group. The RT data now fall into a more linearly increasing curve; however, the slope is only 4 msec. per stroke, but in an analysis of variance, the effect of the number of strokes does not reach significance ($F(4,12)=2.76$, $0.05<p<.1$) (see Figure 8). As in the previous experiments, the average duration per stroke does not show a linear increase, nor a significant main effect.

The correlational analysis shows the same picture as the one of Experiment 2, with adjacent stroke pairs having negative mean correlations and non-adjacent stroke pairs having positive mean correlations, indicating that again these straight-line segments or patterns may be treated as separate strokes.

Figure 7 Average length per stroke as a function of the number of stroke in Experiment 3.

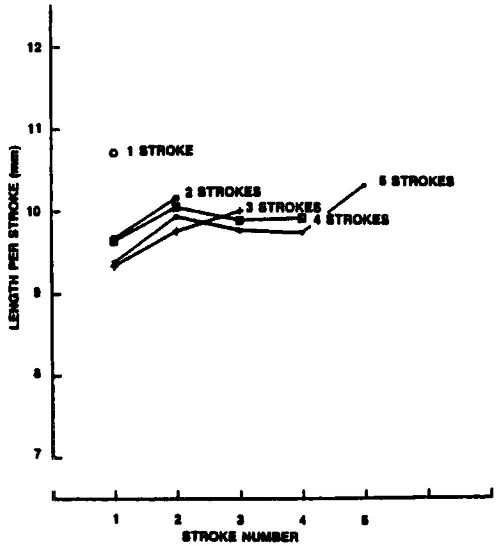
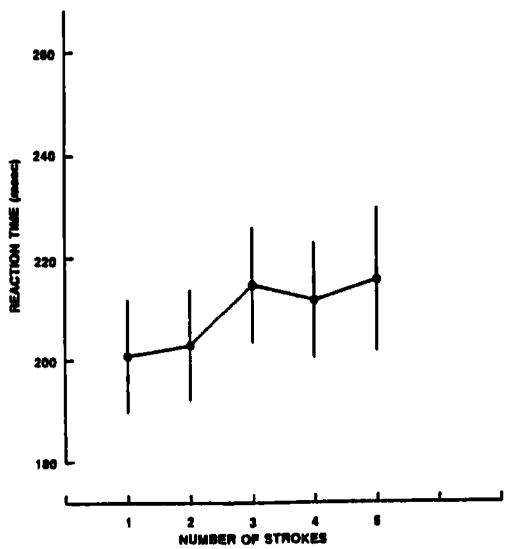


Figure 8 Average RT as a function of the number of strokes in Experiment 3. Vertical bars represent the standard deviations of the means.



GENERAL DISCUSSION

Although Hulstijn and Van Galan (1983) did find a small RT increase as a function of the number of letters, and the present experiments only demonstrate a very weak RT increase as a function of the number of strokes, both studies have failed to find an increase in the average element duration as a function of the number of elements in the writing pattern. This latter result is contrary to that reported by Sternberg, et al. (1983) and would seem to indicate that their subprogram-retrieval and command model of motor programming proposed for speech and typing may not be applicable to handwriting. As suggested in the introduction, an explanation for the absence of element duration effects and robust RT effects might be that in handwriting, planning ahead is not needed due to the narrow frequency handwidth of the physiological system for handwriting. By the third experiment, subjects were producing strokes of relatively homogeneous length at an average rate of 135 msec. per stroke. Compared to 100-msec. element durations for speech and typing, this is a relatively slow rate of motor output. On the other hand, RT is comparable among all tasks. Apparently, even in maximum speed performance tasks, as reported here, handwriting may never reach a speed where planning an entire sequence in advance is more efficient than programming "on-line."

Though there is some sign of a linear trend in RT in Experiments 2 and 3, it does not produce strong evidence for the existence of a motor program for the whole sequence as controlling the execution of each production unit. It may be possible, however, that manipulation of the units has actually confounded RT effects. As the production unit becomes more elemental, i.e., more easily separable into distinct component parts, RT effects become more evident. The continuous nature of handwriting may be proposed as the limiting factor, where even a single down-stroke can be thought of as continuous in comparison to, say, producing pen-mark dots in an up-and-down movement of pen to paper. It is suspected that RT effects would be more likely to appear under this condition, not unlike the effects found in single-finger tapping (Mullins, in preparation; Semjen, Garcia-Colera, and Requin, 1984). As the production units become less distinct, however, these effects tend to disappear.

As for the identification of elementary production units in handwriting, it would appear from the correlated stroke analysis in Experiment 1 that the continuous nature of the curved line patterns defines the down-stroke as the basic unit. This is understandable, in the sense that there is no clearly defined stopping point for the change in trajectory. However, the correlational analysis for the strokes in Experiments 2 and 3 seems to point to the uni-directional stroke (the downstroke as one, the upstroke as another) as the production unit. It may be the case, as seen in these experiments, that there is no one, single unit of programming in handwriting; instead, the production units may depend upon the form of the output. Indeed, there may be no advance planning of the production units of an entire handwriting sequence, thus their elusive nature.

FOOTNOTES

1. This research was supported in part by grants to George E. Stelmach from the Fulbright Commission and U.S. Public Health Service NS 17421. Appreciation is extended to Professor A. Thomassen for allowing the use of the Psychological Laboratory for data collection and analysis purposes.

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THE INFLUENCE OF CHANGES IN THE EFFECTOR COORDINATE SYSTEM ON HANDWRITING MOVEMENTS

Frans J. Maarse
Lambert R.B. Schomaker
Arnold J.W.M. Thomassen

INTRODUCTION

During the execution of a simple writing or drawing pattern such as a circle, triangle or arrow, consisting of several strokes and lasting approximately two seconds, there is an increasing pressure at the tip of the pen. At 90 percent of the total movement duration pen pressure reaches a maximum (Kao, 1983). In cursive handwriting, the movement duration of short words is comparable to the duration of these simple movements. An increased level of pen pressure across words has likewise been observed (Maarse, Schomaker & Teulings, in prep.). The increase in pressure is often accompanied by a decrease in letter size. This is an intriguing phenomenon, for which no explanation has as yet been attempted. One of the questions that must be answered is to what extent these and similar changes occuring within words are determined by 'peripheral' biomechanical restrictions of the executing effector system, rather than by factors of a more 'central' type. The present study intends to relate this kind of question with the changing mechanical features of the peripheral writing system due to the rotation of the hand during left-to-right movements.

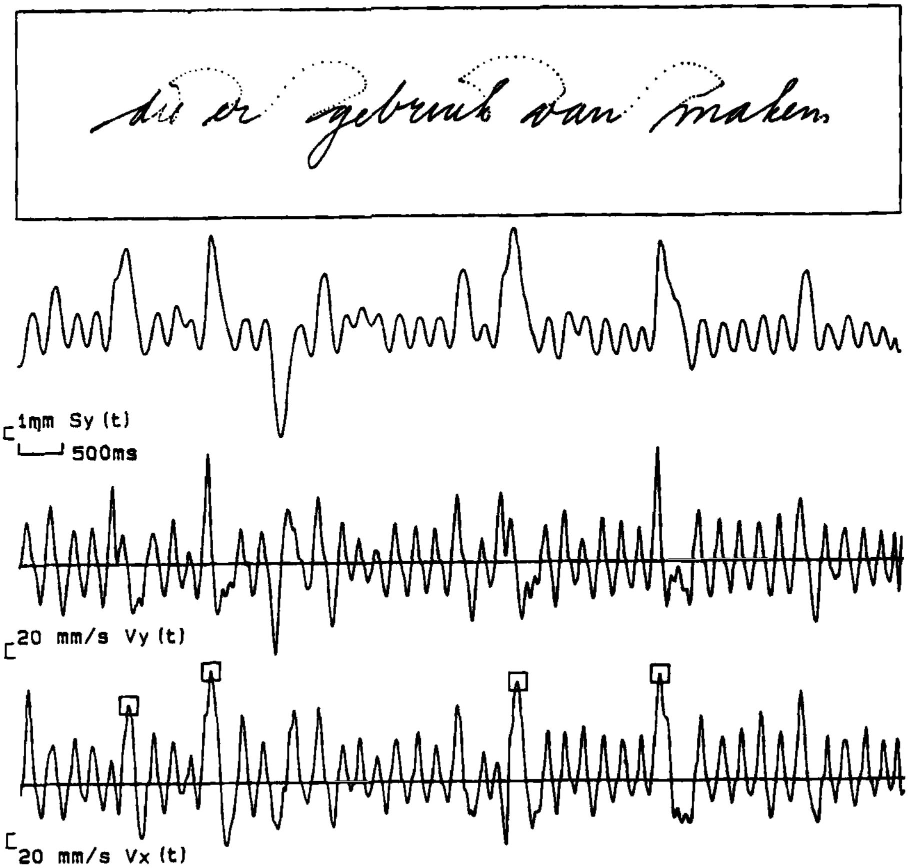
The writing hand can be seen as structured according to two more or less independently operating subsystems (Dooijes, 1984; Hollerbach, 1980). The first system rotates the entire hand about the wrist from radial abduction to ulnar abduction. For small displacements the latter hand rotation may be considered to produce near-linear movements of the pen. In the average writing posture, this subsystem contributes predominantly to the horizontal movement; therefore its principal axis will be labelled X'. The other system consists of the thumb and index and middle fingers. A commonly found range of angles between the two movement directions is from 30 degrees for sketching movements to 70 degrees for writing (Dooijes, 1983). Although the finger subsystem has many more degrees of freedom than the hand subsystem, its preferred movement direction during writing can be established reliably; it is simply derived from the preferred writing slant (Maarse & Thomassen, 1983). The latter direction is assumed to coincide with the principal axis of the finger subsystem and will be labelled Y'. The X'Y' coordinate system which thus reflects biomechanical geometry on the one hand and predominant directions in the writing trace on the other, will generally constitute an oblique coordinate system.

In many right-handed writers it has been observed in our laboratory that between words there is a pen-up movement of the hand to the right, such that the pen position overshoots the starting position of the new word in the X-direction. Meanwhile, the finger subsystem performs an extension which moves the pen-position to a Y-level well exceeding the letter height. This virtual upstroke is followed by a downstroke to the left, also above the paper, until at last the target pen-down position is reached where the production of the next word starts (see Figure 1). It seems as if the hand moves to an optimum position to make the most efficient use of the hand rotation range. In these 'explorative' or 'reset' movements between words much higher velocities are observed than in the writing movements within words.

Interpretation of movement velocity patterns as recorded by the XY orthogonal coordinate system of the handwriting digitizer requires a transformation of the orthogonal coordinates into the oblique X' and Y' coordinates in order to model the described biomechanical geometry. In Figure 2, for instance, it can be seen that the near-vertical downstroke of h could be erroneously interpreted as 'X-activity' if the orthogonal coordinate system is used, whereas, according to the oblique coordinate system it should for its major part be interpreted as non-activity in the X direction. One question now is whether the oblique coordinate system of a certain writer, rotates as a whole as a function of hand rotation, or whether also the angle between X' and Y' coordinates is a function of the rotation of the hand. This is an empirical question that we shall study in the present paper.

After obtaining estimates of the orientation of the axes of the effector coordinate systems for various levels of rotation of the hand it will moreover be possible to transform the orthogonal XY coordinates accordingly and to estimate the contribution of each of the two effector systems under these different hand-rotation conditions. It is hypothesized that spectral bandwidth increases and spectral power amplitude decreases from adduction to abduction, i.e., from left to right. The answer of this second question could then be related to the mentioned decrease of height and writing slant, perhaps as the main causal factor.

Figure 1 Examples of finger and hand movements between words (movements above the paper are represented by dotted lines). The three time functions are: Y coordinate (Sy(t)), vertical and horizontal velocity (Vy(t) and Vx(t)). The square markers indicate extrema in X velocity during pen-up movements.



EXPERIMENT

In the experiment to be described below, subjects are required to produce small near-linear, circular and normal writing movements under various degrees of rotation of the hand. The preferred movement directions as well as the spectral properties of these movements will be studied.

Subjects

Two male and two female subjects, all of whom were right-handed, participated in the experiment. Their ages ranged from 26 to 40 years. They were students and staff of the Department of Experimental Psychology at the University of Nijmegen.

Apparatus and Materials

The handwriting movements were recorded by means of a computer-controlled digitizer (Vector General DT1) with a sampling frequency of 100 Hz and an accuracy of 0.2 mm. The pen tip was an ordinary ballpoint refill.

To eliminate forearm movements, the forearm was placed and fixed in a special-purpose cuff attached to the digitizer, which could be adjusted to the

Figure 2 Comparison of orthogonal and oblique coordinate system for large downstroke in h.

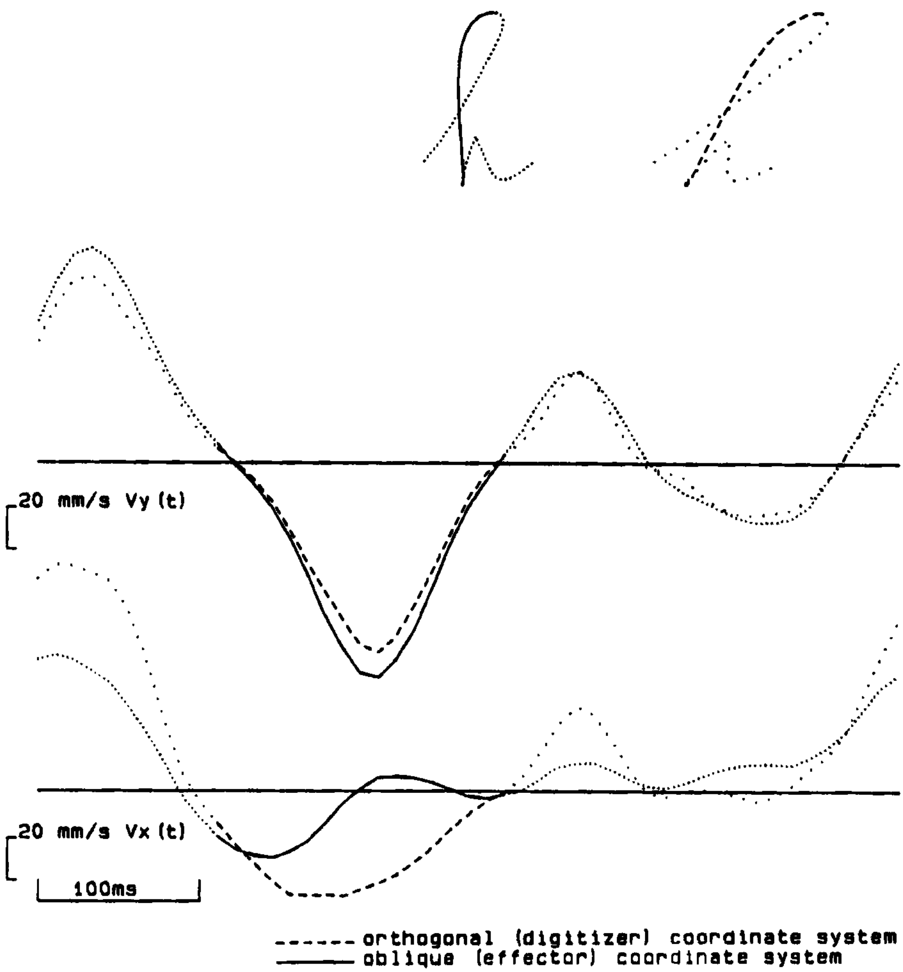


Figure 3 Experimental set-up of XY-tablet (digitizer), forearm cuff, and paper.

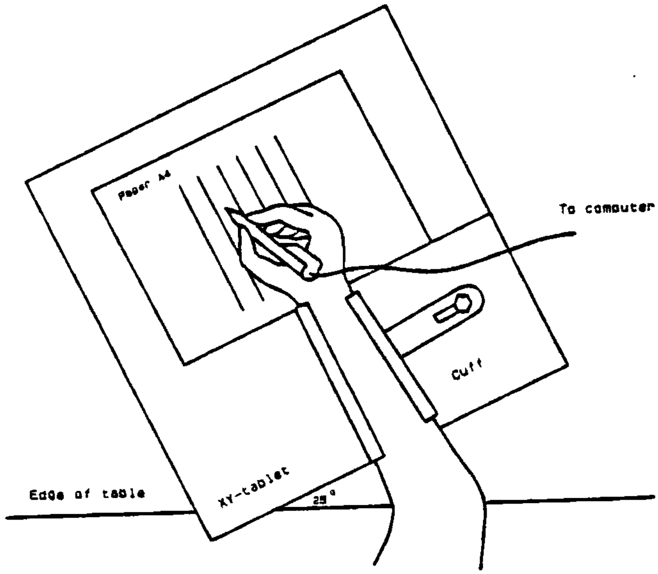
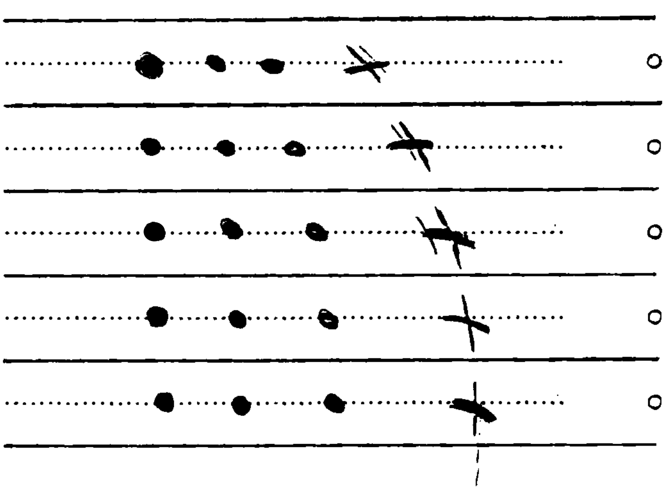
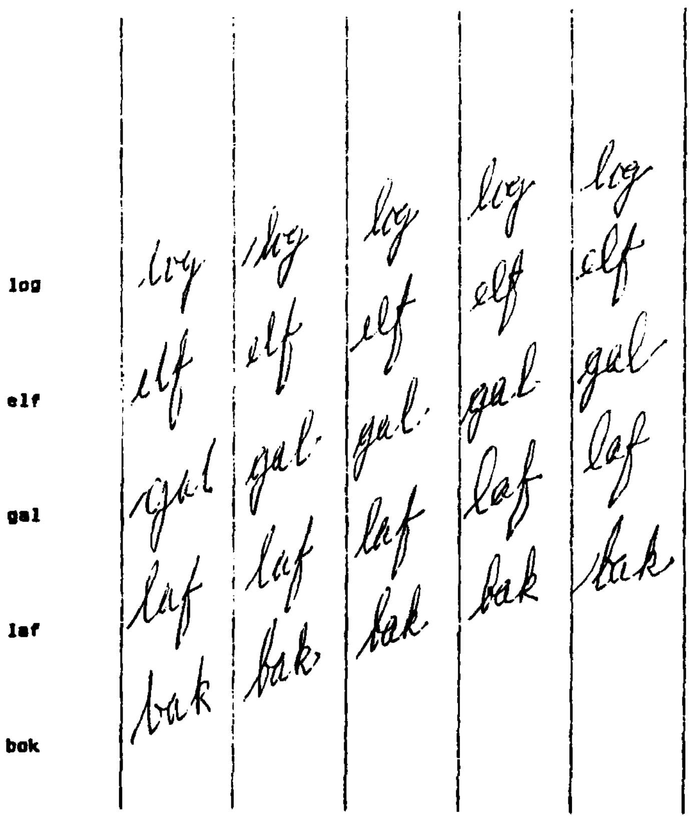


Figure 4 Recorded movements of subject 1. From top to bottom: hand and finger movements (Tasks 1 and 2) and circles of Tasks 3, 4 and 5.



subject's forearm diameter. The forearm was fixed in such a way that its inner side was parallel to the vertical axis of the digitizer. In order to allow free movements of the hand, the ulnar side of the processus styloideus ulnae was just above the top edge of the cuff (see Figure 3). Each task (see below) was performed in five different levels of rotation of the hand ranging from adduction to abduction. The horizontal displacement of the pen from the leftmost to the rightmost position was about 8 cm. With the aid of the cuff the forearm was fixed in such a way that the position corresponded to the normal writing posture of the subject. Standard quality A4-size writing paper was used fixed in a horizontal direction; six vertical lines had been drawn on every response sheet, 20 mm. apart, so that five columns were formed (see Figures 4 and 5). All patterns had to be performed nearby the vertical dotted lines in the middle of the columns. The circles at the top of each column were used as a rough indication of the size of the circular patterns and text to be produced. For every new pattern the paper was shifted about 2 cm. upwards while posture and arm position remained the same.

Figure 5 Recorded words of subject 1 (Task 5).



Procedure

Adjustment Per Subject

After fixation of the forearm, allowing free mobility of the hand, the subject was asked to produce a curved line of about 12 cm. on the paper by moving the hand from left to right and vice versa. The middle of this curve was taken to indicate the midposition of the hand. A response sheet was now brought under the hand in such a way that the middle of the central (third) column on the paper corresponded to the midposition. Instructions about the tasks were then given and the subject was allowed to exercise the task.

Experimental Tasks

All of the following six tasks were performed from left to right in each of the five columns on paper. *Task 1.* Writing small near-horizontal lines with a length of about 3 mm., only using movements of the wrist, not of the finger joints. The lines were written to-and-fro without raising the pen in a self paced preferred rate. *Task 2.* Writing small lines with a length of about 3 mm. by moving only the fingers in a spontaneously adopted preferred near-vertical direction. These movements were also to-and-fro without raising the pen in a self paced preferred rate. *Task 3.* Writing, as fast as possible, circular patterns with a diameter of 3 mm. on the dotted lines. *Task 4.* Writing circular patterns (3 mm.) at a gradually increasing rate. The subjects were asked to follow computer-generated bleeps presented at an increasing rate from 1 to 10 Hz within 20 seconds (50 bleeps). In *Tasks 4 and 5* the subjects were asked to attempt to follow primarily the bleep rate rather than to produce accurate patterns of exactly the required size. Task 5. Writing circular patterns (3 mm.) at a stepwise increasing rate. The presentation rate of the bleeps increased in 8 steps (1, 1.41, 2, 2.8, 4, 5.6, 8 and 11.3 Hz.). In each step lasting 5.12 seconds the writing movements were recorded. *Task 6.* Writing the words log, elf, gal, laf and bok in a normal preferred way.

Data Analysis

At first, all recorded data were filtered in order to remove quantization noise. This was done using the method described by Teulings and Maarse (1984). From the data obtained in Tasks 1 and 2 the preferred X' and Y' directions and frequencies were derived. For determining these directions, the method employed by Maarse and Thomassen (1983) was used.

After calculating the principal movement directions from the data of Task 1, the orthogonal XY coordinates were transformed into the appropiate oblique X'Y' coordinates; this was done separately for each of the five levels of hand rotation, referred to as P1 through P5 below. The obtained oblique coordinates were then differentiated versus time using a five-point finite-differences impulse response (see Dooijes, 1984). The X' an Y' velocity signals were subsequently divided into sample records of 512 samples, tapered with a 10 percent cosine window, following which a Fast Fourier Transform (FFT) was applied. From the FFT functions power-spectral density functions (PSDFs) were calculated (for the data of Task 6 averaged over all five words in each column) separately for the X' and Y' velocity time series. The PSDFs were then smoothed with a rectangular window in order to increase reliability of the individual spectral estimates (Bendat & Piersol, 1971). The number of degrees of freedom for Tasks 2 to 5 are 2x5, and for Task 6 they are 2x5x5. Bandwidth resolution before smoothing was 0.195 Hz. For each PSDF, the median frequency (MF) was calculated in order to express all PSDF information by a single value. The median frequency was used because estimation of peak frequency in a spectrum obtained with FFT is subjected to error. It is assumed that the smoothed spectrum has only one dominant peak.

Results

Table 1 presents the angles of the X'- and Y'-coordinates at each of in the five levels of rotation for the four subjects. Data are expressed with respect to the (orthogonal) X axis of the digitizer. The angle between the direction of X and the table edge is about 25 degrees. The directions of Y' and X' decrease from left to right at approximately the same rate with the exception of Subject 2, who performed her finger movements in Task 2 more or less independently from her hand rotation and more or less constantly in the direction of the writing slant. The angle between Y' and X' appears to be relatively constant only for the subjects 1, 3, and 4.

Table 2 shows the preferred frequencies of the two systems. The preferred frequency of a system is the spontaneously adopted frequency in which the system can operate at optimum speed in a relaxed manner. It can be seen that the frequencies are again nearly independent of levels of hand rotation, and, surprisingly, that they differ only slightly between the hand and the finger systems. Also for Task 3 (circles) the preferred frequencies for the X' as well as for the Y' system are about equal to the preferred frequencies of the separate systems (Task 1 and Task 2). This holds for each of the four subjects.

Because the FFT-analysis of the data obtained from Task 4 leads to essentially the same results as the analysis of the data from Task 5, only the data from the latter, more reliable task are presented here. Figure 6 shows the relation between the eight values of the input frequency (pacing rate) and the output frequency (writing rate) in Task 5. For frequencies lower than the preferred frequency the median output frequency is slightly higher than the target frequency. For pacing rates above the preferred frequency, the median value of the output frequency is much lower than the input frequency. See Figure 6. Figure 7 presents the coherence between the pacing signal and the handwriting output signal of Task 6. Coherence is determined from the PSDFs of the pacing signal (input) and the writing signal (output) and the cross-spectral density function. Its value is high if the ratio between the amplitude and the phase difference are constant. Coherence appears to be relatively high below the preferred frequency and very low above this frequency. Apparently, the subject can easily follow the set pace below the preferred frequency where the phase difference remains about constant. For frequencies around the preferred frequency the amplitude is about constant, but the phase is varying. This leads to a decrease in the coherence around the preferred frequency.

Table 1 Directions of X'-and Y'-subsystems in five rotation levels of the hand (degrees).

	Levels of hand rotation									
	Left				Middle				Right	
	P1		P2		P3		P4		P5	
Subject	X'	Y'	X'	Y'	X'	Y'	X'	Y'	X'	Y'
1	41.3	100.0	29.0	88.6	20.9	71.3	9.0	67.1	—0.5	59.6
2	29.9	82.6	21.3	81.7	14.8	81.2	5.8	80.2	3.5	72.7
3	32.6	52.2	18.9	49.7	11.7	47.1	4.0	36.5	0.3	29.1
4	30.0	75.6	22.4	58.5	14.5	54.4	7.7	44.4	4.6	37.3

Table 2 Preferred frequencies X', Y' and X'Y'-system (Hz).

		Levels of hand rotation				
		Left		Middle		Right
	Subject	P1	P2	P3	P4	P5
X' system Task 1 (Hand)	1	4.214	4.317	4.314	4.419	4.393
	2	4.875	5.338	5.197	5.200	5.239
	3	4.916	5.266	4.875	5.211	5.113
	4	4.935	4.743	4.728	4.668	4.661
Y' system Task 2 (Fingers)	1	4.427	4.176	4.122	4.123	4.112
	2	5.258	5.261	5.139	4.898	4.993
	3	4.713	4.461	4.357	4.452	4.306
	4	4.480	4.370	4.360	4.337	4.289
X' system Task 3 (Hand)	1	4.702	4.569	4.576	4.590	4.635
	2	5.146	5.309	5.167	5.063	5.053
	3	4.137	4.277	4.257	4.381	4.189
	4	4.917	4.819	4.783	4.699	4.722
Y' system Task 3 (Fingers)	1	4.701	4.586	4.534	4.558	4.605
	2	5.178	5.288	5.152	5.107	5.098
	3	4.128	4.260	4.240	4.361	4.171
	4	4.907	4.796	4.738	4.652	4.660

Figure 6 Median of output frequencies versus pacing input frequencies for all four subjects in five positions of the hand for the Y' system. Data obtained from Task 5.

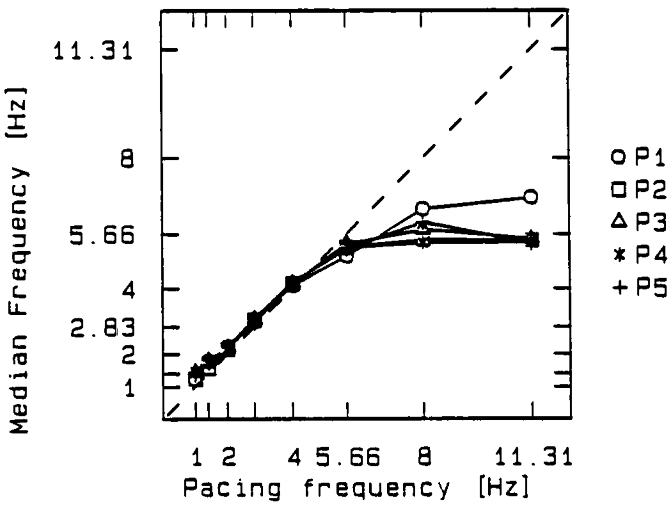


Figure 7 Coherence between pacing sine and Y' velocity for the five rotation levels (Data pooled over four subjects).

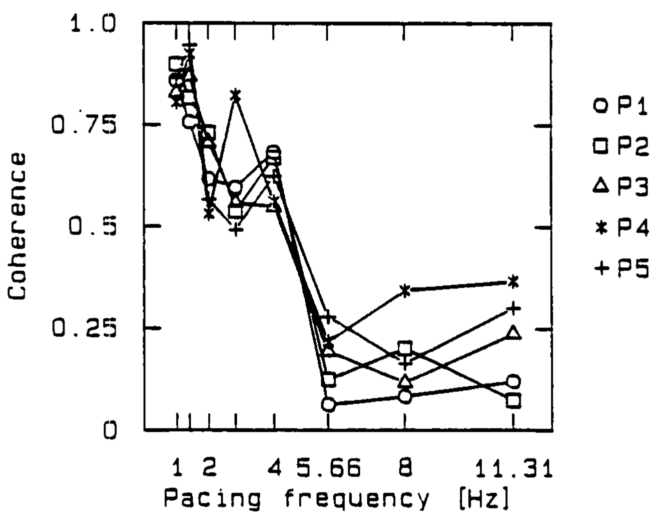


Table 3 Slant of words in five rotation levels (degrees).

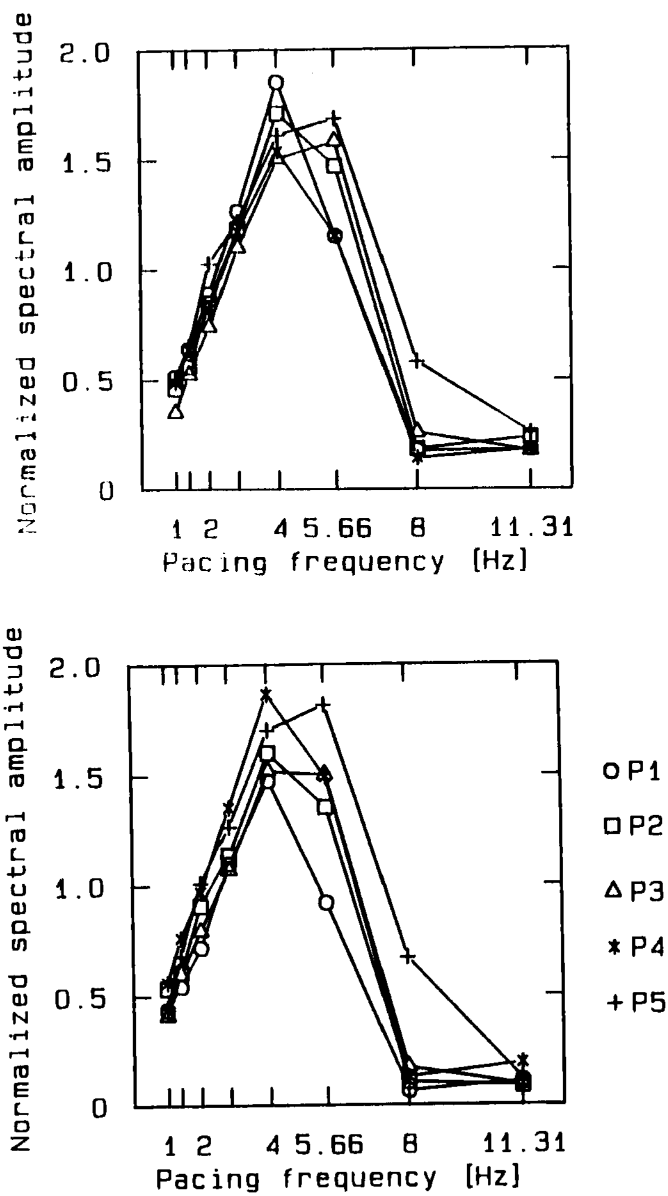
	Levels of hand rotation				
Subject	Left P1	P2	Middle P3	P4	Right P5
1	79.1	75.8	72.4	73.0	69.3
2	95.9	91.3	89.8	80.9	77.6
3	89.0	82.4	78.1	72.8	64.1
4	62.7	56.2	48.3	44.7	39.6

Table 3 presents the slant of the written words (Task 6) for the five rotation levels of the hand. It is clear that the difference between the slant of the written words is nearer to the direction of the Y' system than to the direction of the X' system. The match, however is far from perfect. We shall come back to this issue in the discussion. The direction of the Y' system is varying from left to right (see Table 1). The slant also declines but often at a lower rate. FFT analysis of the speed in both X' and Y' direction shows that the bandwidth of the spectra varies only slightly across the five positions. See Figure 8. Looking at the power spectra, however, we observe an interesting change (see Table 4). The spectra of X' appears to decrease going from left to right whereas those of Y' increase to nearly the same extent. This implies that, although the preferred frequency of hand and finger movements remains approximately constant across the levels of hand rotation there is a tendency for the fingers to play an increasing part in the production of the writing trace at the cost of the hand as this is abducted from left to right.

Table 4 Power of X' and Y' systems in the five rotation levels of the hand (Relative power).

		Level of hand rotation				
	Subject	Left P1	P2	Middle P3	P4	Right P5
X' system (Hand)	1	31.1	20.0	8.2	4.9	5.3
	2	14.1	10.8	8.9	6.5	7.6
	3	8.2	8.4	8.3	18.1	31.1
	4	4.1	3.9	3.0	2.7	0.7
Y' system (Fingers)	1	12.6	17.3	22.5	29.7	37.6
	2	9.7	8.5	10.7	11.1	12.6
	3	18.8	25.6	26.5	45.3	65.7
	4	1.3	2.6	2.7	3.6	1.8

Figure 8 Normalized averaged spectral amplitude of speed in X' direction (left) and Y' direction (right). Data from Task 6 pooled over four subjects and five words per positions.



Normalized averaged spectral amplitude
L=Vx' R=Vy'

DISCUSSION

The preferred frequencies are only slightly affected by rotation of the hand. The obtained figures of the preferred frequencies (in the order of 4.5 Hz) compare well with the peak value in the spectrum of handwriting found by Teulings and Maarse (1984). At first sight, it may be surprising that the preferred frequencies for X' and Y' differ only slightly, because one would have expected that two mechanically so different systems would have different resonance frequencies as already found by McAllister (1900). One explanation is that there is common refractoriness of some kind of the order of 220 ms. Another explanation, requiring a learning process of higher order, could be that writing movements are made within a small frequency range corresponding best to their combined mechanics. Consequently, they are well trained and overlearned together, which might generalize to their operation in isolation. Whatever the explanation, of the observation that the subsystems have their own preferred frequencies we may expect that the modal durations of movements of certain simple curved patterns will be more or less constant. This agrees with the findings by Thomassen and Teulings (1985) and by Viviani and Terzuolo (1980).

The results thus indicate that the writing subsystems are nonlinear because in the output there appear new frequencies which were not offered at the input. These systems can be therefore be looked upon as badly performing 'phase locked loop' systems. Within a certain range, the input frequency is always followed, but outside this range synchronisation breaks down and responding settles on a maximum frequency of about 5 Hz.

The fact that the output spectra of X' and Y' in varied hand rotation positions change strongly in opposite directions, implies that in cases of fixated forearm the writing from left to right is increasingly performed by the Y' system, or by the finger movements. This situation also arises during the writing of a word where normally the forearm is kept still. It was observed that also in the constrained writing conditions of Task 6 subjects tend to keep writing slant more constant than would be expected from their spontaneous finger movements under these conditions. A similar slant constancy was obtained by Maarse and Thomassen (1983) when they varied the left to right (X) progression by instructing the subjects to write with narrower or wider spacing. Under these conditions the constancy could be explained in terms of preferred Y'-directions, which, in principle, may remain constant under varied progression. The writing slant changes in the present experiment, however, are considerably smaller than the orientation changes of the Y' system. Thus we must conclude that writing slant under these conditions does not follow the Y' direction.

The implication of these results for normal writing is that within a word, when the pen is not raised, and the forearm kept still, writing slant is held constant by an intricate interaction among the X' and Y' subsystems. This requires a much more complicated, and more centrally organized system than the mere preference of relatively simple effector systems.

As regards the decreasing height of handwriting (between pen-lifts) in a word, we must conclude that the increasing role of finger movements towards the end of a word would not predict a decreasing vertical size, because this is mainly achieved by the movement amplitude. A higher order explanation may be that the increased force requirement due to an overall stiffness of hand-and-fingers is likely to trade off against linguistic redundancy towards the end of the word.

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HANDWRITING PRESSURE: EFFECTS OF TASK COMPLEXITY, CONTROL MODE AND ORTHOGRAPHIC DIFFERENCE

Henry S.R. Kao
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INTRODUCTION

Handwriting is a complex psychomotor task relatively unaffected by the environment (Thomassen & Teulings, 1983). It mostly involves the control and coordination of the muscles of fingers, hand and arm, subject to visual guidance and monitoring, and requires the simultaneous monitoring of the flexion or extension of thumb and fingers of the writing hand and the abduction and adduction of the hand around the wrist joint (Van Galen & Teulings, 1983).

In addition to physical parameters, handwriting also involves behavioural variables: writing time, speed and pressure underlining the dynamic control processes. Of particular interest in this line of investigation has been the recent studies on writing pressure associated with different writing tasks (Schneider, 1975; Kao, 1981a, 1981b, 1983, 1984; Kao, Shek & Lee, 1983; Kao & Shek, 1985; Shek, Kao & Chau, 1985). Furthermore, fundamental psychological processes of perception, motion and cognition are dynamically integrated in the motor act of handwriting. Investigations along these lines are important to provide psychological insights into handwriting.

For handwriting tasks relative to the visual stimuli for writing three different modes of control have been suggested: tracing, copying and freehand (Kao, Shek & Lee, 1983). The differences among these modes rest with the differential of control precision as well as associated visual-cognitive involvement. Kao and Shek (1985) identified several grounds on which tracing and freehand modes could be differentiated. Firstly, the referent stimuli were externally represented for the tracing mode but internally represented as images for the freehand writing. Secondly, the task requirements for tracing were more rigid and well-defined in the criterion for following the specific writing path than for the freehand mode. Thirdly, it may be likely the three modes involve different mechanisms of information processing.

The first comparison of handwriting pressure between control modes was done by Kao, Shek and Lee (1983). They concluded that exertion of pressure in writing tasks involving different levels of task complexity did not vary when conducted in the tracing mode, but were affected by task complexity in the freehand mode. These findings suggested a difference between the two modes (i.e., complexity independency *vs* dependency hypotheses). A later experiment by Kao, Shek, Lam and Guo (1984) showed that subjects' heartrate changes and respiratory activities varied relative to the three modes of handwriting control; and, also suggested different aspects of information processing systems were required.

A formal investigation of the control modes in handwriting was done by Kao and Shek (1986). In practising Chinese calligraphy, significant differences in heartrate deceleration and writing time were found between these three modes: respiratory activity showing no difference. In another experiment comparing copying and tracing modes (Shek, Kao & Chau, 1985), there was no difference in reaction latencies to probe stimuli. However, higher writing pressure and longer writing time were associated with the tracing mode suggesting that the muscular activities demanded of respective processes may be different. These two recent studies have amplified the differentiation of these various modes of control in handwriting.

The relationship between visual stimulus patterns and the motor control performance is another important aspect of handwriting behaviour. The variations in the patterning of visual configurations could possibly shed some light on the understanding of the ongoing cognitive motor process in handwriting. Hung and Tzeng (1981) compared the difference in reading behaviour of three languages, Chinese, English and Japanese, and concluded that orthographic variations affected our reading behaviour, and different cognitive systems were required for achieving reading proficiency in different languages. Although the cognitive systems in reading and writing behaviour may not be the same, it can be suggested from such findings that different writing systems from different languages, due to the perceptual-cognitive-motor mechanism involved, also affect writing behaviour. Cross-language comparisons of writing behaviour have been conducted between English and Hebrew (Goodnow, Friedman, Bernbaum & Lehman, 1973) and Hebrew and Arabic (Lieblich, Ninio & Kugelmass, 1975), showing orthographic differences leading to writing behaviours specific to the writing system of the language.

In comparing Chinese handwriting and the writing of English words, Wong (1982) found that the former resulted in greater writing pressure than the latter. This difference was further supported in a study by Kao, Shek & Lee (1983) showing the tracing of lines, simulating Chinese handwriting, to lead to greater writing pressure than the tracing of circles which simulated English words. When writing pressure, writing time and arm EMG activities were used as dependent variables to differentiate writing in Chinese from that in English, Kao's (1984) findings supported the effect of orthographic variations on writing pressure.

The interplay of perceptual and motor mechanisms during handwriting appeared further mediated by another important element, the cognitive processes (Kerr, 1983) in which the visual information processing appeared dependent on a 'central decisional mechanism,' the extent of whose operation relates to the degree of precision required by the particular motor task and the particular task portion (Stelmach & Hughes, 1983). Research in this area has been limited. A recent study by Kao (1983) reported an interesting intra-task, inter-trial pattern of pressure variations for repeated writing tasks. This pattern, called the Progressive Motion Variability (PMV), indicated that in repeated performance of continuous handwriting tasks, such as drawing lines or writing strings of letters writing pressure throughout the writing task and across the repetitions, followed a progressively increasing trend, from the beginning to the end of the task, with the peak located just near the termination point of the task. Two related studies (Kao, 1981a, 1981b) comparing writing performance of normal and the spastic and athetoidic subjects have supported the generality of the PMV curve for normal subjects. One explanation suggested for such a phenomenon was that greater precision control and increasing reliance on visuo-motor feedback became progressively more demanding toward the termination of the task (Kao, 1983).

With respect to a cognitive interpretation of the PMV phenomenon in handwriting and drawing, a central decisional mechanism has been postulated as related to the attentional capacity and motor control involved in the writing act. It has been suggested, when more attention should be paid to decision-making activities based on feedback from the progress of writing and action relative to the terminal targets of the writing tasks, the higher the writing pressure and pressure variability accompanied by such increased attentional demands. Empirical validation of this relationship has yet to be formally conducted.

The brief review of several important parameters in handwriting above laid the groundwork for the present research. The first aim of the present study was to further compare the effect of orthographic differences between Chinese and English on the motor task performance in handwriting. It was observed that both inter-orthography and intra-orthography variations could be differentiated in both languages (Kao, 1984). In the present study, regular style of Chinese characters, consisting of discrete strokes (mostly straight in form) and requiring various directional changes in writing movement, were used. Particularly evident in the longhand style of handwriting, English words consisted of more circular and cursive strokes than Chinese. For the present experiment, English words in longhand style were used as experimental tasks.

The first objective of this experiment using both writing systems to define the levels of complexity was to test the relationship between writing pressure and task complexity. Task complexity was operationalised in terms of number of strokes for Chinese characters. For English words complexity was operationalized by number of letters and by the distance of pen-tip travel and number of turnings movements. A study by Wong (1982) showed that in copying Chinese characters, there was a tendency for more complex characters to result in lighter writing pressure. Kao (1984) reported a tendency for increased number of strokes in Chinese characters to relate to lighter writing pressure. Using number of strokes to define complexity, Shek, Kao and Chau (1985) also found a significant effect of task complexity on Chinese handwriting. These studies have consistently found that writing of more complex figures has been associated with lighter writing pressure. This part of the present experiment attempted to further test the relationship between task complexity and task performance by varying task complexity at five levels both in the Chinese and English.

A second focus of the experiment was concerned with the PMV phenomenon which was found in writing and drawing tasks using the tracing mode of task motion (Kao, 1983). The question remained whether or not the PMV phenomenon would also occur in other modes of control and in tasks other than writing graphic configurations. Therefore, two other modes of handwriting control, copying and freehand, and two different orthographies, Chinese and English, were used in the present experiment.

The third purpose, using writing pressure and pressure variability as dependent variables, was to further differentiate the three modes of handwriting control. It was conjectured that different cognitive processes were involved in these modes of control; and, thus, it they would be empirically reflected by variations in these two variables. It was expected, on the basis of previous findings (Kao, 1983), that the higher the degree of attentional demand among the three control modes of task execution, the higher writing pressure and the intra-task pressure variability. One particular point deserving notice was a claim by Shek, Kao and Chau (1985) that even though processing capacity might be allocated for specific motor initiation and execution purpose, leading to higher pressure in tracing mode due to greater task requirement, some processing capacity might also be allocated to the copying task. Capacity allocated to the copying task might also be used for different purposes. The freehand mode of handwriting control, being different from the other two modes in terms of external attentional requirement, was hypothesized to require less writing pressure and pressure variability.

Finally, the experiment was also designed to further test the complexity-independency hypothesis proposed for the tracing mode and the complexity-dependency hypothesis for the freehand mode of handwriting control (Kao, Shek & Lee, 1983). The former stated that in single tracing tasks, there would be no difference in the writing pressure between the more and less complex tasks. On the other hand, the latter stated that writing pressure would be related to task complexity in the freehand mode, and that the more complex the task, the greater would be the writing pressure. Because the two hypotheses were suggested on the basis of writing tasks with graphic figures and English words performed in two separate experiments, a more systematic test of these hypotheses was necessary. In this respect, the third mode of handwriting control, copying mode, was introduced. This control mode was expected, from an attentional allocation perspective, to lie somewhere between the freehand and tracing modes in writing pressure and pressure variability.

METHOD

Subjects

A total of 24 subjects, 8 male and 16 female students taking courses in Psychology, were used in this experiment. They were all English-Chinese bilinguals, and had not taken part in any similar experiments before. Each subject completed the experimental tasks in one session.

Apparatus

A modified model of electronic handwriting analyser that had been used in previous research (Kao, 1983) was used together with a microcomputer, an IBM PC, for this experiment. The pressure tranducer, in the form of an aluminium plate at a size of 53×17.5 cm. was fixed onto the center of a writing platform. The same ball-point pen was used by all subjects. The writing pressure data were recorded for any period of time that the pen was in contact with the tranducer plate with a minimum pressure exertion of 1 gram to trigger the recorder. Data points of the pentip pressure on the tranducer were sampled at a rate of 7 milliseconds and stored on the magnetic diskettes for later processing and analysis.

Design and Stimuli

The experiment was conducted in two parts. In the first part, subjects were required to complete two writing tasks, using the tracing mode of handwriting control. There were two types of stimulus figures for the writing tasks, each consisting of 5 figures in Chinese and in English, as illustrated in Figure 1. The task figures were arranged from right to left in ascending order of complexity defined in terms of the number of strokes or letters for Chinese and English respectively (Kao, 1984). Because it was a typical character consisting of 8 different types of strokes in Chinese handwriting, the Chinese character '永' was chosen as a stimulus word. Similarly, because it included a number of English letters with different stroke movements, the English word 'shown' was chosen. The first 12 subjects traced the Chinese stimuli first followed by the English ones, and the other 12, in the reverse order.

Figure 1 Chinese and English stimuli in 5 levels of complexity.

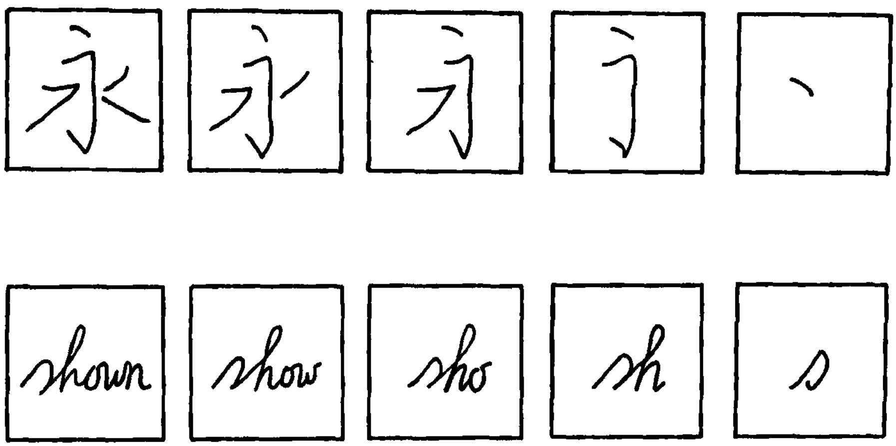
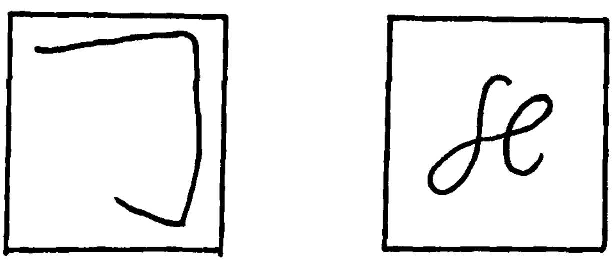


Figure 2 Linear and cursive stimuli.



In the second part, a two by three within-subject design was adopted for the two independent variables of stimulus types and control modes. There were two stimulus types, the 'linear' figures and the 'cursive' figures, and three modes of handwriting control, the 'tracing,' 'copying' and 'freehand' modes (Figure 3). Totally, each subject performed the 6 writing tasks with the following combinations of stimulus patterns: tracing-linear (TL), copying-linear (CL), freehand-linear (FL), tracing-cursive (TC), copying-cursive (CC), and freehand-cursive (FC).

The writing paths of both types of writing stimuli were 6.7 cm. long. The linear configuration was used to simulate Chinese characters. Each of which was made up of two radicals, the (一) and (乛). The cursive configuration, simulating English words, was made up of the letters 's' and 'e' in longhand form. Both configurations were printed in the same length and boxed by a square of 2.5×2.5 cm. These stimulus figures were printed on writing paper placed on the pressure tranducer or presented to the subjects for reference for the writing tasks. By a Latin Square design, subjects were randomly divided into 6 groups of four each.

Procedure

Before the experiment, instructions were given to subjects on writing in the three different modes of handwriting control on the writing platform. For the 'copying' and 'tracing' modes, they were told to write in their normal handwriting speed, and conform to the presented stimulus figures as much as possible. A practice period of three minutes was given to all subjects to familiarize them with the writing equipment and the task requirements for the first part of the experiment. Each subject had to trace each of the 5 stimulus patterns 5 times on a piece of thin typing paper.

For the second part of the experiment, the subjects were instructed to write the 6 different stimulus patterns, arranged in randomized order, 15 times each. In the tracing mode, the stimuli were placed on top of the tranducer plate. Subjects traced the patterns in the squares printed on the paper placed over the tranducer plate. In the other two modes, a blank sheet of paper was placed on the plate for the writing tasks. The stimulus patterns were presented in front on paper to the side of the subject at a distance of 20" for the copying mode of control. But for freehand writing, they were presented to the subjects for 15 seconds, by the experimenter, before their actual task performance. Signals of 'ready' and 'start' were also used, as in the first part, for subject's task execution.

Data Analysis

In part one of the experiment, the sum of values of the data points was divided by the number of points for each trial to obtain the mean pressure score. The 5 scores for each stimulus pattern, forming a trial, were averaged, representing the pressure rate in each level of complexity. ANOVA tests were performed to compare the 5 levels of task complexity in the writing of Chinese and English.

The data in writing each stimulus pattern per trial in part two of the experiment were divided into ten equal segments (Kao, 1983). The mean pressure score and its standard deviation across the 15 task repetitions for each of the 10 segments were calculated. These scores for both the linear and cursive writing patterns for each subject formed the basis of data analysis of the PMV phenomenon. The overall mean pressure and pressure variability scores across the 6 stimulus patterns for each and all subjects were also computed for the comparison of the effect of the stimuli types and the modes of handwriting control on writing task performance.

RESULTS

In part one of the experiment, ANOVA tests revealed that the differences between the mean pressure rates for different levels of task complexity were significant both for the Chinese and the English stimulus patterns, $F(4,92)=46.52$, $p<.01$ and $F(4,92)=11.84$, $p<.01$ respectively.

Figure 3 Mean writing pressure for 5 levels of task complexity in Chinese writing.

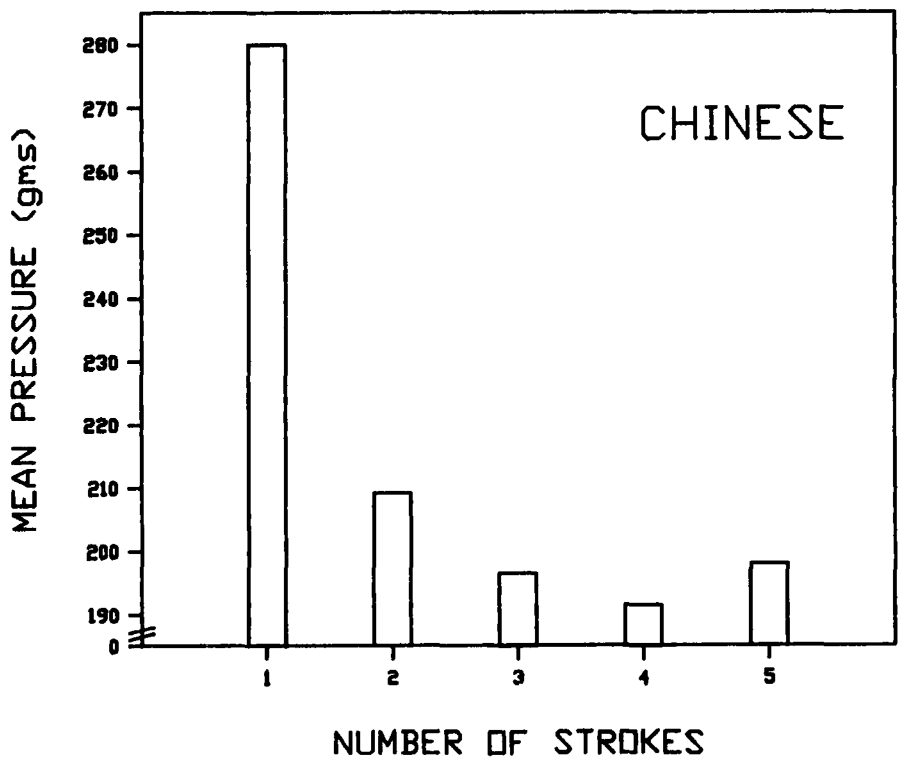
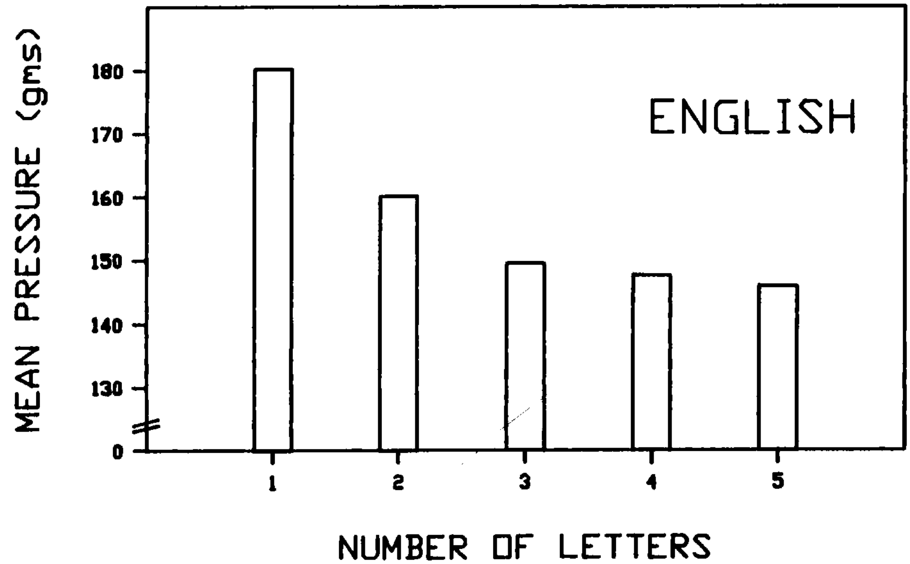


Figure 4 Mean pressure for 5 levels of tasks complexity in English writing.



Figures 3 and 4 show that for the writing of both the Chinese and English word patterns, there is a clear trend for the mean writing pressure to decrease with increasing levels of task complexity. Except that between levels 2 and 5 in the Chinese writing task, analyses revealed levels 1 and 2 of the task complexity were statistically different from all other levels at a minimum of 0.05 confidence level for English and Chinese writing tasks. These findings supported the view of an inverse relationship between task complexity and writing pressure in the writing of English and Chinese words. The most salient feature was the comparison of simple task configurations (level 1) with all other levels of complexity. Configurations that were more complex showed small differences among themselves. Furthermore, a comparison between the 2 sets of stimuli in the two languages revealed that the mean writing pressure for Chinese characters was significantly higher than that for English words ($F(1,23)=8.71$, $p<0.01$).

The statistical analyses for the second part of the experiment are summarized in Table 1. Figures 6-11 illustrate the curves for the mean writing pressure and pressure variablility for each of the 6 writing tasks, while Figure 5 graphically presents these two curves for all tasks combined. Except for the only insignificant difference in pressure variability for the task of TC (tracing-cursive), results indicated the PMV phenomenon was clearly evident. For both writing pressure and pressure variability which increased towards the termination of the writing task, there was an ascending intra-task trend in all 6 tasks. These curves also applied when the 6 tasks were combined. For these curves, the peak level of PMV occurred at either the 9th or the 10th segment of the task performed, a finding consistent with those in the original study on PMV in handwriting pressure which indicated that in repeated writing or drawing tasks, the subject's pressure exertion became progressively larger especially in the later portions of task movement; and, the task pressure variability was greatest near the termination of the task movement (Kao, 1983). This phenomenon in the present experiment was found for both the linear and the cursive patterns of stimulus under three different modes of handwriting control.

Figure 5 Intra-task mean pressure and pressure variability throughout the 10 segments of the task averaged across all 6 writing tasks.

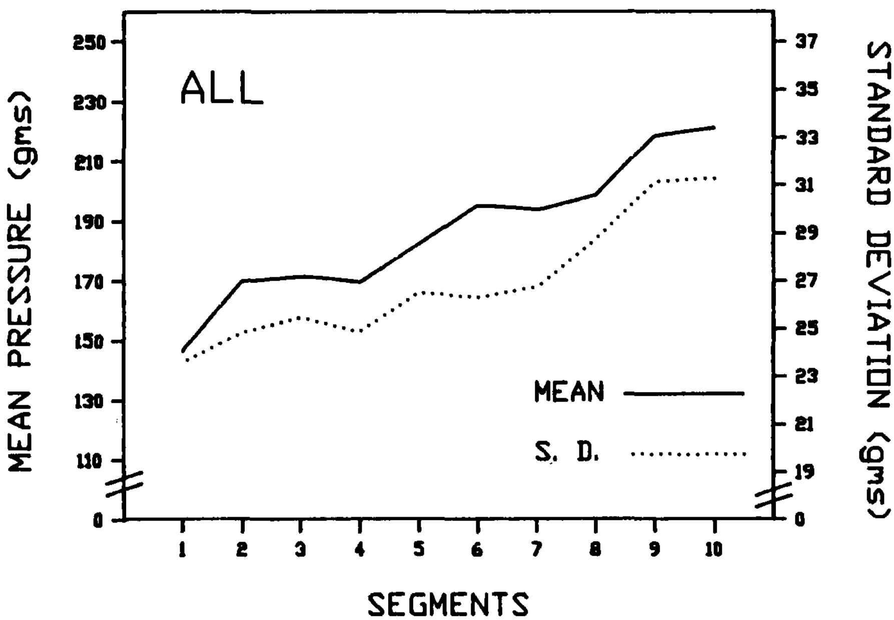


Figure 6 Intra-task mean pressure and pressure variability throughout the 10 segments in the freehand-linear task.

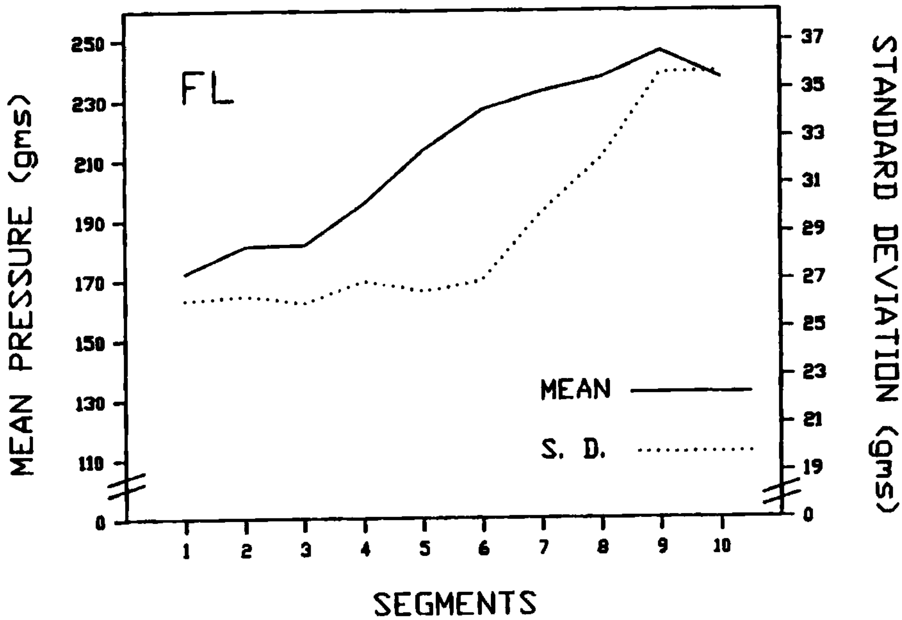


Figure 7 Intra-task mean pressure and pressure variability throughout the 10 segments in the copying-linear task.

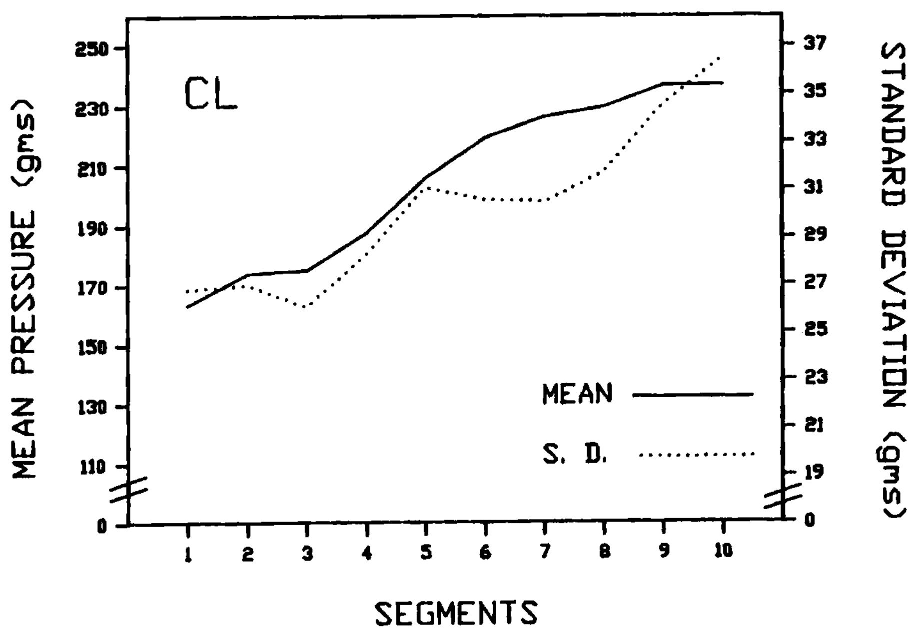


Figure 8 Intra-task mean pressure and pressure variability throughout the 10 segments in the tracing-linear task.

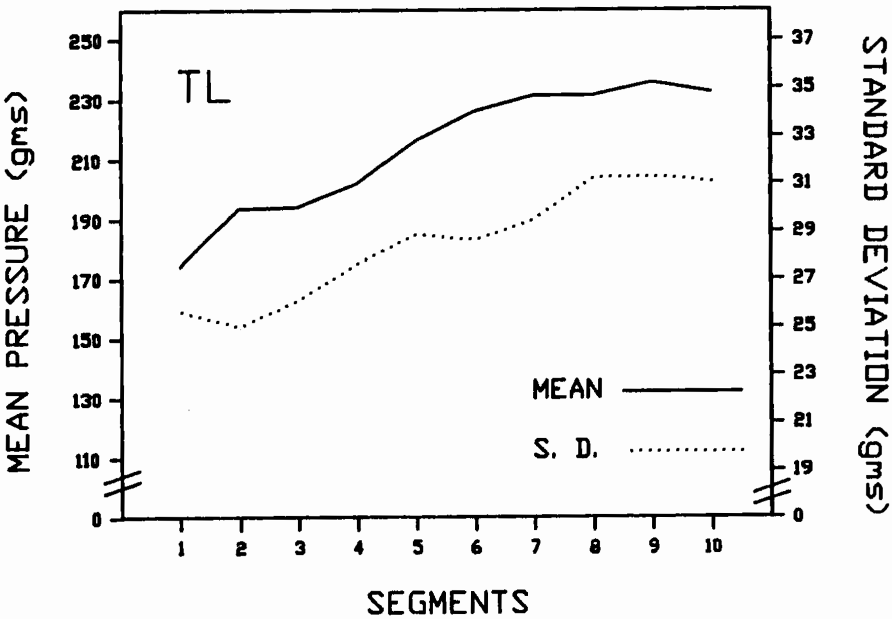


Figure 9 Intra-task mean pressure and pressure variability throughout the 10 segments in the tracing-cursive task.

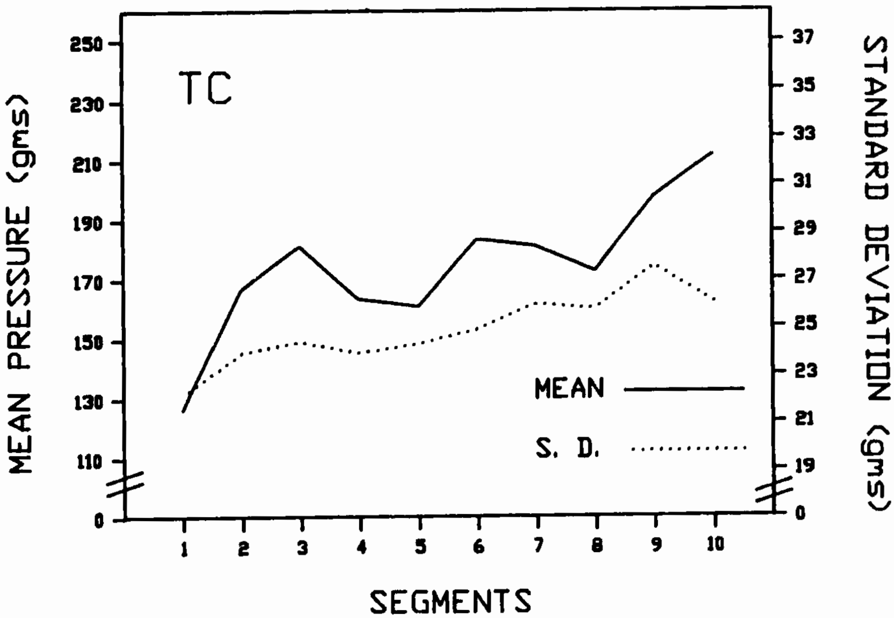


Figure 10 Intra-task mean pressure and pressure variability throughout the 10 segments in the copying-cursive task.

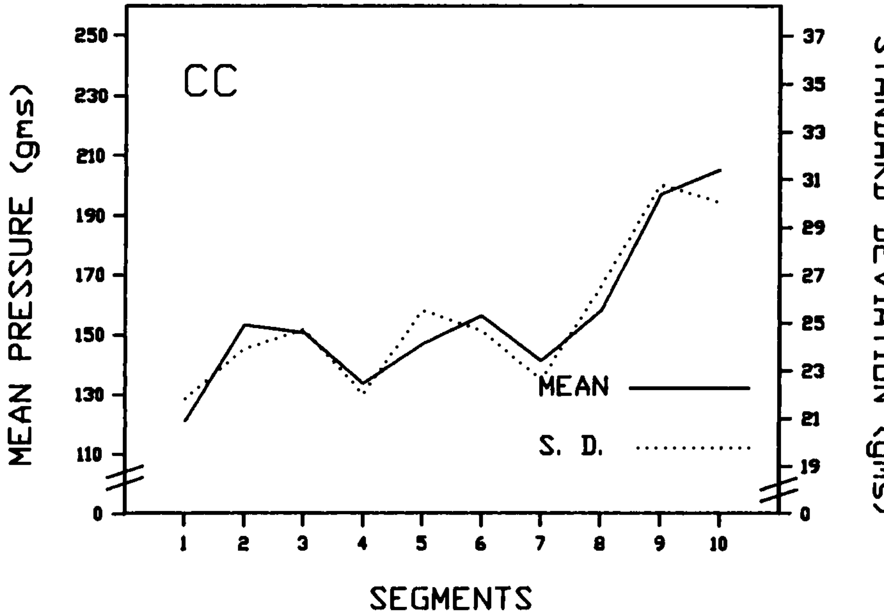


Figure 11 Intra-task mean pressure and pressure variability throughout the 10 segments in the freehand-cursive task.

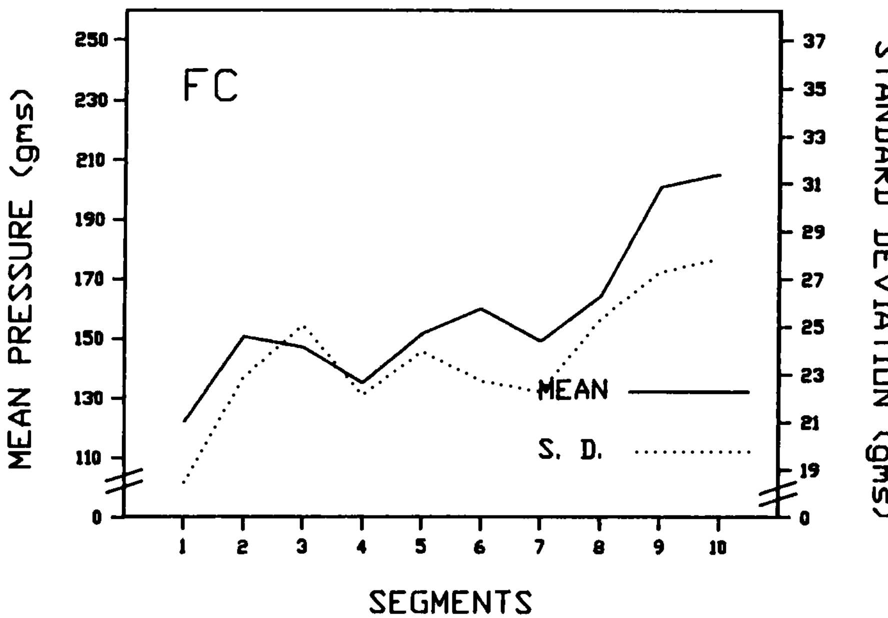


Table 1 Results of ANOVA tests on the difference in mean pressure and pressure variability among the 10 segments of the various writing tasks.

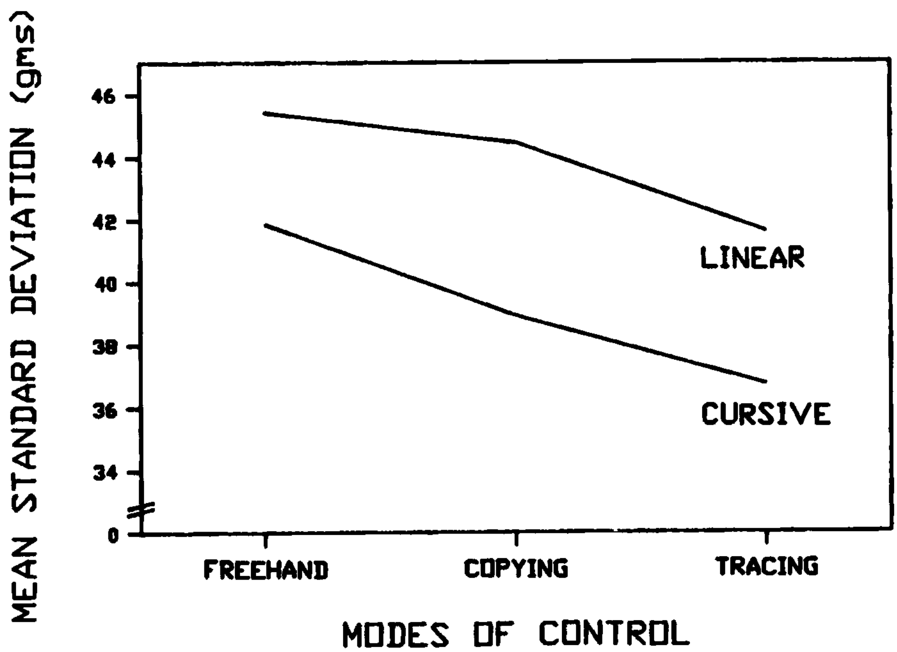
Writing Task	Mean Pressure (F-values)	Pressure Variability F-values)
Freehand-linear	F(9,198)=36.64**	F(9,198)= 6.24**
Copying-linear	F(9,198)=35.09**	F(9,198)= 5.55**
Tracing-linear	F(9,198)=16.94**	F(9,198)= 2.76*
Freehand-cursive	F(9,198)=31.70**	F(9,198)= 5.00**
Copying-cursive	F(9,198)=45.63**	F(9,198)= 5.58**
Tracing-cursive	F(9,198)=36.91**	F(9,198)= 1.72
All Tasks	F(9,198)=67.63**	F(9,198)=13.82**

* p<0.05
** p<0.001

The ANOVA results on mean pressure scores showed a significant main effect of stimulus patterns, (F(1,22)=41.90, p<.01), between the linear and cursive tasks. These findings confirmed the findings in the first part of this experiment that writing linear and angular figures (Chinese writing task) resulted in greater writing pressure than the cursive and circular ones (English writing task), so that the difference in writing pressure between the two types of writing systems was a significant factor affecting the motor task performance. However, the main effect of control modes (F(2,44)=2.58, p>.05) and the interaction effect (F(2,44)=1.71, p>.05) were not statistically significant. Further analysis by t-tests showed that in writing cursive patterns, the mean pressure for tracing mode was greater than that of the copying mode (t(22)=1.76, p<.05) and the freehand mode (t(22)=2.23, p<.05).

Another 2-way ANOVA test of mean standard deviation scores for pressure variability in the 10 segments showed significant main effects for both the stimulus patterns (F(1,22)=9.02, p<.01) and the modes of handwriting control, (F(2,44)=3.78, p<.05). But the interaction effect was insignificant (F(2,44)=0.42, p<.05). The results are depicted graphically in Figure 12. It was evident that pressure variability was greater for the linear than for the circular writing tasks, a result supporting the role of orthographic differences in affecting handwriting performance. As to the effect of different modes of handwriting control on pressure variability no significant difference was found for the three modes. However, there was a general trend for freehand writing to result in greater pressure variability than the copying and tracing modes. T-tests showed that for both linear and cursive writing patterns, freehand mode had greater mean pressure variability than tracing (t(22)=1.84, p<.05) and copying (t(22)=1.93, p<.05). Greater pressure variability was also found for the freehand writing of cursive patterns than for the copying mode (t(22)=1.91, p<.05).

Figure 12 Results of 2-way ANOVA test of mean standard deviation scores in the 6 tasks.



DISCUSSION

Three factors governing the dynamic processes of handwriting, the writing pressure, the modes of control and the visual stimulus variations, have been examined. Of special interest in this study was the effect of the latter two variables on writing pressure and writing pressure variability. Certain interesting results were found which may have general implications for understanding handwriting behaviour.

The first finding was that motor task complexity was found to have a significant effect on the exertion of pressure in handwriting. For both the Chinese and English writing systems, writing task complexity in terms of the number of strokes or letters was found to be inversely related to writing pressure exerted in the tracing mode. This result was consistent with previous findings concerning the effect of task complexity on writing pressure in tracing and copying Chinese characters (Wong, 1982; Kao, 1984; Shek, Kao & Chau, 1985). Since the present study also examined handwriting pressure in the writing of both Chinese and English, these findings extended such a relationship to the English writing system, which has different spatial characteristics from Chinese orthography (Kao, 1984). In this part of the experiment, the lengths of the stimulus path were varied to provide cues for the guidance of handwriting movement and to reflect different levels of attentional demands. The results of this experiment further supported the view that different handwriting systems such as Chinese and English might involve different levels of attention, which may influence the motor programming on energy expenditure for handwriting. Thus, it is conjectured, increased motor efforts in the task execution might inhibit the exertion of force in the writing motion.

Under the assumption of limited channel capacity, the amount of attention paid to the motor task per unit length in the task stimuli should decrease as a function of the size of the stimulus which would result in lighter pressure for a smaller stimulus than for a larger stimulus. This expectation has been substantiated by the present findings on the basis of the difference found between the two orthographies. Therefore, it may be said that perceptual variations are mediated by such cognitive changes associated with attention. Thus it seems reasonable manipulation in simple motor tasks, such as writing at lower levels of task complexity, may involve more intensive motor control than for more complex tasks. The finding of a trend for the task pressure to decrease as a function of task complexity was especially salient when simple tasks are compared with more complex tasks. The differences among the latter tasks being progressively reduced. The latter result may account for the inability to find significant differences in writing pressure among configurations in Kao, Shek and Lee, (1983) involving the tracing mode of handwriting control.

An alternative interpretation of such a phenomenon was proposed by Shek, Kao and Chau's (1985), 'initial adjustment' hypothesis. It stated in order to benefit the latter portion of the writing task, initial motor adjustment was required to stablize the writing effort in the beginning portion. Therefore, the mean overall pressure rate was reduced with increased length of writing. Moreover, the study of writing interruptions by these author's might also give explanations to such finding. Similar to the above interpretation, it was suggested that preparation for latter strokes was done parallel to the execution of the earlier strokes, thus leading to greater effort in muscular control facilitating the latter strokes. Similarly, the finding of Hulstijn and Van Galen (1983) that longer reaction time was required for one letter than for two letters demonstrated the existence of preprogramming, which was linked to the finding of facilitation for the more complex tasks. These various possibilities represent the possible interpretation of the finding as an inverse relationship between writing pressure and task complexity.

Another major finding of the study was the differential effect of orthographic variations between English and Chinese on writing pressure and pressure variability in writing task control. As in the first part of the experiment, writing pressure was higher for Chinese characters than for English words. But when linear and cursive configurations were introduced as stimulus patterns both writing pressure and the pressure variability were found to be greater for the writing of the linear over the cursive configurations. These findings may also be explained by attentional allocation mechanisms discussed previously. Based upon the differential spatial characteristics of the two writing systems, and because circular movements are more natural than linear movements (Goodnow, Friedman, Bernbaum & Lehman, 1973), it would appear that two distinctive motor control mechanisms may operate. This implies a lower level of attentional requirement and muscular control than for linear writing. English handwriting represented by the cursive writing in this experiment, was characterised as consisting mainly of continuous and circular movements leading to smaller force and greater pressure stability than the linear writing, while the angular and linear Chinese writing has, as a result, led to greater writing pressure and pressure variability. It was clear that the effect of orthographic variations on handwriting pressure and pressure variability in the present study further substantiated and extended previous findings (Kao, 1984) from simple tasks to the handwriting of both orthographies.

The PMV phenomenon was found for all six writing tasks in the second part of the experiment including the writing of linear and cursive forms in each of the three control modes. Distributions of the intra-task mean pressure rates and pressure variability were in agreement with the results found in Kao (1983). The location of the peak level of variability occurred invariably at the 9th or the 10th segment of the task course, a finding closely resembling the past finding that the peak location occurred uniformly at the 9th segment or the termination point. These results lend further support to the previous suggestion that PMV was a general phenomenon, to be expected in various handwriting tasks. The significance of the present findings indicated the PMV phenomenon has been substantiated not only for handwriting tasks under the tracing mode of control and for the cursive stimulus pattern, but also for the freehand and the copying modes of the control in both linear and cursive forms of handwriting tasks.

The visuo-motor feedback mechanism appeared to be central to the occurrence of the PMV phenomenon. Visual information obtained from the written traces served as the reference for the subsequent motor responses. The intensity of the operation of this central decisional mechanism was, however, not uniform in the progression of the task. The most critical segment of the task was when approaching the termination point, where relatively more decisions were progressively required until the final moments of the task duration for precise task termination. Generally, greater effort was expected in muscular control activities when attentional demand for precision became progressively intensified as the closure point of termination drew the attention of the writer. When the task was performed repeatedly, showing a distribution of a progressively ascending trend, the effect on pressure variability at particular point of the task appeared accumulated.

One particular characteristic apparent from the PMV phenomenon was a tendency for both the pressure and pressure variability to be greater in cursive than linear writing. The reasons for such a tendency needs to be examined in future studies. However, it may be reasonable to assume that these differences are attributable to the nature of the two writing systems investigated, particularly the variations in the visual and spatial characteristics as well as the associated motor control mechanisms.

The results on the effect of control modes were less encouraging. There was no significant difference in the main effect for the mean writing pressure. However, pressure variability was found to be larger in the freehand mode and smaller in the tracing mode, a finding suggesting there may be differential attentional mechanisms for specific modes of handwriting control. Further analyses comparing the experimental tasks showed a quite different picture. Although the effect of control modes on mean writing pressure was not salient in the linear task patterns, the differentiation was larger in the cursive task patterns, particularly in the tracing and the freehand modes of control. The comparison of pressure variability for various writing tasks also confirmed such an effect. The actual effect on both the pressure and pressure variability in handwriting between cursive and linear writing tasks under the copying mode of control was not substantiated; thus, further experimental testing may be useful.

The significant effect of complexity on writing pressure in the tracing mode in the first part and the significant effect of stimuli patterns effect in the second part of the experiment did not support the complexity-independency hypothesis suggested by Kao, Shek and Lee (1983). This finding is consistent with similar recent observations of Shek, Kao and Chau (1985), which showed that writing pressure enlarged with increased complexity in handwriting tasks. Therefore, the question of orthography — specificity in handwriting pressure variations as a function of task complexity remains an intriguing question deserving further experimental verification.

The theoretical perspective of handwriting was investigated in this research from the standpoint of perceptual cognitive-motor systems domain of handwriting. Since handwriting control demands a high degree of precision and accuracy in the patterning of motor output, in the various forms of written materials, it seemed particularly important for the feedback mechanism to direct the motor responses. In this experiment, the handwriting acts were conceptualised as an integrative process of perception, motion and cognition. Of the three, it seemed that the cognitive element was a major determinant of the efficiency of visuo-motor coordination. It was assumed that the cognitive element in visual information processing was dominant in the course of control motion related to a postulated attentional capacity. The findings in this study were largely substantiations of expectation from past researches.

FOOTNOTES

1. This paper was planned for the 2nd International Symposium on the Neural and Motor Aspects of Handwriting, but not presented due to tight symposium schedule. It was subsequently invited for this volume. The authors thank Drs. D. Shek and N. Murphy for helpful comments on the manuscript.

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Overview

There are a number of ways in which the study of children's handwriting could provide valuable information. Capturing many of the psychomotor performances before they were overlearned, there was a better opportunity to study the formative elements of the behaviours. Putting the behaviours in perspective, the study of the evolution of mature handwriting behaviours enhanced our understanding. The paper by Meulenbroek and van Galen investigated the microstructure of the production of strokes of children from grades 1 to 3. In repetitive copying of patterns, the following variables were studied: sequence length, degree of continuity, direction of rotation, writing size, speed instruction, and height constraint. Dependent variables included movement time, movement distance, mean and maximum velocity of each stroke. Changes in the preparatory cursive writing behaviour of these young children as a result of increasing age and as a result of different size, speed-accuracy, and lineature instructions were discussed. In general, non-monotonic development of performances was found. Compared with adult controls, the children were also found to profit from rehearsal more and follow a more piecemeal strategy of strokes.

The paper by Sassoon, Nimmo-Smith and Wing examined the penholds of pupils ranging in age from 7 to 15 years. It showed that a systematic description of penholds was workable and revealed some significant findings. Although the proportion would expand to three quarters if the "modified tripod" penhold was included, only one third of the subjects at each level adopted the strict "dynamic tripod" penhold generally advocated by teachers. However, there seemed to be little difference in terms of speed of writing whether subjects adopted the conventional, modal penhold features or not. Legibility was not examined in this study. Differences between left and right handers, in terms of paper orientation and position, were reported — and differences tended to increase with age. Other age related changes were also noted. A majority of the subjects were found to write with their thumbs closest to the pen tip, contrary to the direction of writing manuals prescribing the index finger instead. Finally, a method of appraising the relative contributions of finger, wrist and arm movements to the movements of pen-point were outlined.

The remaining two contributions in this Section dealt with aspects of pathology and remediation, particularly in younger children. The prediction of learning problems, identification of the nature of problems, as well as indications of effective remediation were all explored in these papers. The importance of top-down processes in the control of handwriting was again demonstrated. Simner investigated the correlation between form errors produced by pre-kindergarten and kindergarten children, as determined by the Printing Performance School Readiness Test (PPSRT) and school performance in a follow-up study done from one to three years later. Correlations ranged from 0.4 to 0.8. The interscorer reliability and test-retest reliability of the PPSRT itself was high. The PPSRT should prove to be a useful early warning indicator of learning disability. Supplementary studies, such as providing findings that tracing performance tended to be better than copying and that copying performance was better than printing from memory immediately after seeing the letters or numbers, suggested that the nature of the problem of form errors might not be perceptual/motor. Instead, possibly indicating different approaches to remediation, it was suggested that momentary lapses in attention to detail or the lack of familiarity with letters and numbers might be responsible.

The paper by Søvik, Arntzen, and Thygesen reported on the effects of a training program on the handwriting of both normal and dysgraphic children. While it was generally agreed that feedback was important in any training, including handwriting training, the proposed program involves "social tracking": with the child doing a tracking task in cooperation with an instructor. Both sensory feedback and "supplementary feedback" (arising from the interactions between the instructor's input and the child's sensory feedback during the task) were presented in the new situation. When compared with control subjects, both the accuracy and smoothness of the writing of these children were significantly improved without any sacrifice of writing speed. There was also some indication that the dysgraphic children might benefit from the program more than ordinary children. It was suggested that social tracking is preferable to computer-assisted instruction.

Graphonomics: Contemporary Research in Handwriting
H.S.R. Kao, G.P. van Galen, R. Hoosain (eds.)

MOVEMENT ANALYSIS OF REPETITIVE WRITING BEHAVIOUR OF FIRST, SECOND AND THIRD GRADE PRIMARY SCHOOL CHILDREN

Ruud G.J. Meulenbroek
Gerard P. van Galen

INTRODUCTION

Skill Development

Learning to write is a complex process in which the development of cognitive functions and the motor system plays an important role (Thomassen & Teulings, 1983). In general, skill development may be characterized by a gradual incorporation of the microstructure of the skill into an overall plan or action programme (Kay, 1970; Bruner, 1970). It is this conception which led to the introduction of repetitive writing patterns as preparatory cursive writing exercises in writing curricula of the last few decades because these patterns visually reflect, and motorically practice, the repetition of isolated cursive letter components. In the course of preparatory cursive writing education writing patterns are being practised in progressively smaller sizes with more distal parts of the body, following the general maturational direction of motor development from proximal to distal (Gesell, 1940). The development of the component processes of the handwriting skill has not been studied very extensively. Especially the microstructure of the stroke production process has hardly ever been considered from a developmental standpoint. Analyses of the dynamic characteristics (movement time, movement distance, mean and maximum velocities) of adult handwriting have shown that strokes consist of regular patterns of bursts of energy of agonist and antagonist muscle groups separated by silent, ballistic intervals. In adults the production of writing strokes is a very well learned ballistic procedure. In a study on the development of eye-hand coordination Hay (1979, 1984) described the relation between the programming and guiding system as follows. Reaching movements are performed in a ballistic way in

5-year-old children and controlled by a guidance system in 7-year-olds, whereas the integration of both systems is being acquired at a later age. The study of Hay on eye-hand coordination as well as the studies of Von Hofsten (1979, 1980) on reaching behaviour in infants and the studies of Mounoud, et al. (1985) on manual tracking skills of 5-to 9-year-old boys, showed that motor development probably does not coincide with monotonically increasing performance.

Recently it has been reported that the acquisition of the handwriting skill might occur in discontinuous stages as well (Wann, 1985). If the writing task is considered as a series of composite 'aiming' movements we may expect that the mastery of stroke production may also exhibit a discontinuous change of movement strategies. The young child at the age of 5 or 6 is supposed to be fairly well skilled in producing drawing strokes of greater size in a ballistic manner (Hay, 1979, 1984; Thomassen & Teulings, 1983; Mounoud, 1985). In learning to write the child has to produce smaller and more continuous patterns involving the more distal parts of the musculature of the hand and fingers (Thomassen & Teulings, 1983). These learning procedures urge the child to perform visually controlled pen movements. Only after this period of visual monitoring of handwriting the child regains control of a ballistic strategy (Wann, 1985), at a higher speed level and with a better mastery of the smaller letter forms. It was the aim of the present study to observe in detail changes in the quality of stroke production of children of the first three grades of primary school. We used copying tasks which were varied on a number of motoric variables. These were: (a) the length of the writing pattern, (b) the character of the stroke connections: continuous versus discontinuous and (c) the direction of rotation of strokes. Furthermore we studied the effects of (d) size variations of the copying patterns, (e) effects of speed and accuracy instructions and (f) effects of lineature constraints. We not only investigated the effects of these variables on traditional performance measures such as movement time, movement distance, mean and maximum velocities but also the quality of stroke production by analysing the frequency spectra of the velocity data in terms of their signal-to-noise-ratio. The latter measure may be considered to reflect the contribution of slow, intermediate and high frequency components in the movement pattern and thus may serve as a measure of the degree of ballistic strategies within writing performance.

Sequence Length

Several authors have used the effects of length of a movement pattern to study the relation between programming of the task and the demand structure of the execution of the task (Sternberg, Monsell, Knoll & Wright, 1978; Hulstijn & Van Galen, 1983). These and other experiments have shown that, in adults, higher order codes are programmed in advance whereas details, especially those which are context dependent, are programmed in the course of movement execution (Klapp and Wyatt, 1976; Sternberg, et al., 1978; Van Galen, Meulenbroek & Hylkema, 1985). One of the developmental headlines of motor skill development is that children of increasing age are more able to detect and code the higher order structure of a movement pattern (Kay, 1970; Bruner, 1970). Kay (1970) emphasized the need for a child to acquire control over his own responses, preferably in sequential units of considerable size. We therefore hypothesized that performance of repetitive writing patterns would be enhanced if the number of repetitions in the writing pattern increases presumably because practicing earlier components of the long pattern provides the child enough training to increase his writing speed of the later components and therefore the mean overall velocity of the pattern. In our experiment we varied the length of the copying patterns and predicted that longer patterns would be realized with faster performance measures.

Degree of Continuity

Cursive writing seems to have a continuous character compared to the more discrete fashion in which manuscript letters are being produced. Reaction and movement time analyses (Van Galen & Teulings, 1983; Van Galen & Van der Plaats, 1984), however, have shown that before and during cursive writing a number of independent psychomotoric processes take place within the adult subject. A plan for action has to be retrieved or constructed from memory or perception in which in an abstract manner goals for movement are being set. Then, depending on the task requirements, the proper movement parameters, like writing size, speed and inclination, must be chosen. A last prerequisite for starting writing movements is the proper anatomic adjustment of motor units, muscles, hand and fingers in order to be able to realize the goals for movement in an ongoing changing environment. Adult writing movements show fast ballistic characteristics which implies that linguistical and psychomotoric processes take place in a parallel manner (Van Galen and Van der Plaats, 1985). Young children write rather slowly and therefore they realize different writing sizes, speeds and inclinations in a different way than adults do (Meulenbroek, et al., 1985). They also have to learn the right anatomical positions in which the writing task can be completed with relative ease. Discontinuous writing patterns contain a number of acute angles. These angles elicit movement stops, which give the young child an opportunity to prepare the upcoming trajectory (Wann & Jones, in press). In these stops the child may take some time for planning the next point on the paper to move to, to choose the right size, speed and inclination of the upcoming trajectory and meanwhile adjust its hand and fingers into an optimal writing posture. In discontinuous writing patterns the preparation and execution of movements may take place in a sequential manner whereas in continuous patterns preparation has to take place while execution is going on. The writing patterns under investigation varied in degree of continuity. The stroke connections of three of the patterns had a continous character (no acute angles) and the stroke connections of the other three patterns had a discontinuous character (acute angles) (see Figure 1). We predicted that stroke production of discontinuous patterns would be faster and of a higher quality than of continuous patterns because these latter patterns require preparation and organization of upcoming strokes during the actual course of a stroke.

Direction of Rotation

For the greater part cursive letters are formed by anti-clockwise writing movements. Thomassen & Teulings (1979) have shown that in free scribbling tasks young children (aged 6) spontaneously drew more clockwise movements than anti-clockwise. In fast drawing tasks children and adults performed clockwise rotations faster than anti-clockwise rotations, whereas this relation was reversed for slower writing tasks. In these latter 'graphemic' tasks the velocity of anti-clockwise movements increased with age. The experimenters proposed two ways in which the motor system can behave, one addressed as fast 'non-graphemic' drawing tasks, depending heavily on extension movements, and the other addressed as slower 'graphemic' writing tasks depending predominantly on flexion movements. In our experiment subjects had to perform clockand anti-clockwise writing patterns and patterns with an alternating direction of rotation. The writing patterns consisted of letter elements which are superimposed on a steady progression from left-to-right. We therefore considered the task a 'graphemic' one and predicted that anti-clockwise patterns would have faster movement characteristics than clockwise patterns and that patterns in which the direction of rotation alternated would be performed with the slowest performance measures.

Writing Size

In adults the size of writing is not directly proportional to the time required for its production (Katz, 1951; Denier van der Gon & Thuring, 1965; Michel, 1971; De Jong, 1979). The same letters in different sizes are written with minimal changes in temporal patterning but with varying force amplitude. In fast 'non-graphemic' tasks young children realize different writing sizes by means of varying force amplitudes as well (De Jong, 1979; Teulings, et al., 1980), whereas in relatively slow and complex 'graphemic' and drawing tasks they require significantly longer writing times for larger writing sizes (Meulenbroek, et al., 1985). In our experiment repetetive writing patterns had to be written in different sizes. We predicted that although large patterns would be realized with higher mean and maximum velocities than small patterns, they would require more writing time as well.

Speed Instruction and Height Constraint

Traditionally, education has heavily emphasized neatness in writing performance. If speed instructions are followed up properly it can be expected that movement patterns become more ballistic. These ballistic movement patterns are characterized by rapid acceleration and deceleration, high peak velocities and little velocity changes (Meulenbroek, et al., 1985; Wann, 1985). We therefore predicted that speed instructions should result in higher signal-to-noise ratios corresponding with a higher quality of stroke production. A last question of our experiment concerned the effect of different lineature conditions on writing performance measures. It was hypothesized that the presence of a constraint on writing height would slow down writing performance and cause lower signal-to-noise ratios when the subjects were pressed to write very accurately, because the monitoring of the goal position would take place during the realization of upstrokes. The presence of such a constraint under speed instructions, however, might elicit advance planning of goal positions (Pantina, 1957) resulting in more ballistic movement strategies and higher qualities of stroke production.

METHOD

Subjects

Thirty normal right-handed children from an ordinary Dutch primary school were involved in the experiment. Differences in performance between grades were tested with ten pupils of each of the grades one, two and three. The mean age and standard deviation of ages per grade were as follows. Grade one, mean age 6;11 (dev. 0;3), grade two, mean age 7;6 (dev. 0;3), grade three, mean age 8;9 (dev. 0;9). In each group boys and girls were equally represented. As a control two righthanded female adults served as subjects in the experiment.

Procedure and Apparatus

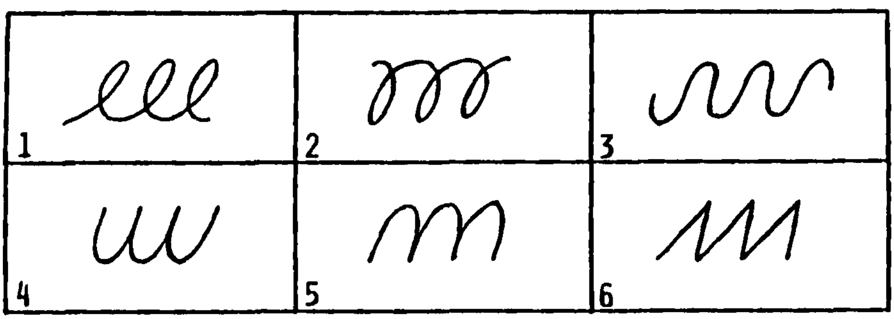
All subjects performed the experiment under equal environmental conditions in an airconditioned, sound-protected van which had been rebuilt for experimental purposes. Each subject was seated on a school chair and in front of a school desk which were appropriate to the subject's length. The writing movements were recorded by means of an Apple-2 XY-tablet and a slightly thicker than normal ballpen which were both attached to an Apple-2 microcomputer. In front of the subject was a tv-monitor on which the writing product was visible after the completion of a writing pattern. The subjects wrote on normal writing paper (format A4) with preprinted lineature, which was fixed to the XY-tablet. The XY-tablet was rotated 15 degrees anti-clockwise to ensure an optimal writing posture. The complete experiment consisted of three tasks, called A, B and C, which were presented to the subjects in a random order, making up a total of forty trials. In each trial the following sequence took place. The experimenter placed a card of 10 × 3 cm. on which a writing pattern was pictured at the upper part of the XY-tablet and at the same time started a trial sequence controlled by the computer. A period of 2 s. followed in which the subject was instructed to observe the writing pattern on the stimulus card. Then a low tone sounded which indicated that the subject could begin to write the pattern. After this low tone the writing movements were recorded during a period of 8 or 12 s., depending upon the length of the pattern, with a sampling rate of 100 Hz. After this sampling period a high tone indicated the end of the trial at which the experimenter removed the stimulus card. Between trials there was a resting period of approximately 20 s. in which the recorded data were stored on a floppy diskette.

Experimental Tasks

Tasks A and B: Length, Degree of Continuity and Direction of Rotation

Task A contained six repetitive writing patterns (see Figure 1) which were replicated twice in a random order leading to twelve experimental trials. Each pattern contained three up and three downstrokes. The height of all patterns was 1.0 cm. Three patterns (patterns 1, 2 & 3) had a continuous character without acute angles, whereas the other three patterns (patterns 4, 5 & 6) were discontinuous. Within the group of continuous patterns the direction of rotation was varied: pattern 1 turned anti-clockwise, pattern 2 turned clockwise and pattern 3 asked for a periodical alternation of clockwise and anti-clockwise pen movements. Within the group of discontinuous patterns again the direction of rotation was varied: pattern 4 consisted of anti-clockwise arcades with starting and stopping points at the upper parts of the strokes; pattern 5 turned clockwise and downwards. In pattern 6, a zig-zag running from left to right, the natural curvature of writing strokes was to be suppressed and straight lines had to be drawn. Task B was identical to Task A except that the length of the patterns was twice the length used in Task A (six up and six downstrokes).

Figure 1 Copying patterns used in the experiment.



The paper on which the subjects wrote in Tasks A and B contained twelve baselines of 5.0 (Task A) or 10.0 cm. (Task B) horizontal length. The vertical distance between these lines was 2.0 cm.

The instruction to the subject was to copy the pattern pictured on the stimulus card in a normal accurate way without interrupting the writing movement.

Task C: Size, Speed-accuracy and Lineature Instructions

For Task C the patterns 1 and 2 (Figure 1) were used with different sizes, speed-accuracy and lineature conditions. *Size* was varied through the presentation of these two patterns in two different heights of 0.75 cm. and 1.50 cm. respectively. *Speed-accuracy* variation meant that in 50% of the trials the subject was pressed to write very fast, while in the other half of the trials accuracy was stressed. *Lineature instruction* was varied through providing the subject in half of the trials an appropriate baseline and upperline on the paper upon which the writing pattern was to be copied. The separation between baseline and upperline was 0.75 cm. or 1.50 cm. according to the size of the stimulus figure.

The instruction to the subject was to copy the picture shown in its proper height on the baseline, making use of the upperline when present, and following the speed or accuracy instructions as given with each writing pattern by the experimenter.

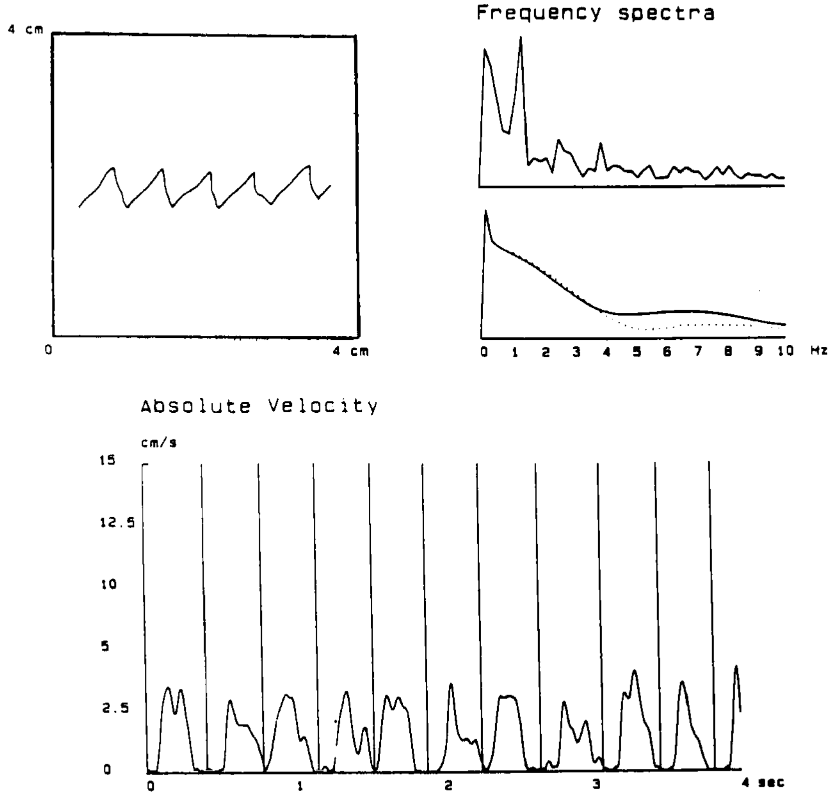
Size, speed-accuracy and lineature conditions of Task C were counterbalanced in order within subjects, and randomly ordered between subjects. Each condition and pattern was replicated once, making up a total of 16 trials for Task C.

Data Analysis

Performance Measures

Data analysis was performed by means of a PDP 11/45 and a VAX-11/750 computer. Each writing pattern was automatically segmented in up and downstrokes according to a vertical position criterion (see Figure 2). Of each stroke the movement time, movement distance, mean and maximum velocity were determined. The data of the first and last stroke of each writing pattern were omitted for further data analysis. For each trial of Task A the performance measures of two up and of two downstrokes were averaged. Of Task B this was done with five up and five downstrokes per trial. The median of these mean performance measures of up and downstrokes of the two replications per task were the cell entries for a two-way analysis of variance to test the effects of the experimental variables grade, length, degree of continuity and direction of rotation. For Task C mean performance measures of two up and of two downstrokes per trial were the cell entries for the analysis of variance to test the effects of grade, direction of rotation, size, speed-accuracy and lineature conditions.

Figure 2 Example of data analysis of a copying sample (upper-left-panel) with corresponding absolute velocity pattern (lower-panel; vertical lines represent stroke-boarders) and optimal scaled amplitude frequency spectra (upper-right-panel): the upper graph represents the spectrum of the whole sample, the lower graph represents the mean spectrum of upstrokes (dotted line) and the mean spectrum of downstrokes (solid line).



Determining the Quality of the Writing Signal

The quality of the writing signal was investigated by determining the amplitude frequency spectra of the absolute velocity pattern of each writing performance (see Thomassen & Teulings, 1979 and Teulings & Maarse, 1984) and by determining these spectra of up and downstrokes separately within four equal frequency bands between 0 and 10 Hz. Since the predominant frequencies of the childrens' writing performance in our experiment (see also Wann and Jones, in press) were in the order of 1.0 Hz, with a standard deviation of 0.5 Hz, it is reasonable to assume that the movement frequencies were within 0 to 5 Hz (see also Teulings and Maarse, 1984). The spectral components between 5 and 10 Hz consequently had to reflect non-controlled fluctuations in the motor system and noise due to the measuring technique. The quotient of the energies in the lower frequency band and in the higher frequency band could therefore be interpreted as a signal-to-noise ratio. As a measure of the quality of stroke production we used the square root of this ratio which we called the signal-to-noise amplitude ratio (SNA-ratio).

RESULTS

Tasks A and B

Grade Differences

The overall mean data and corresponding standard deviations of the movement characteristics per stroke of grade one, two and three and the control subjects are presented in Table 1. Although no significant differences in movement characteristics between grades were found, a general trend was observed in reduced writing size from grade one to three. The variability of the writing product with regard to size and correctly copied form was the largest in grade two, as is reflected by the relatively high standard deviations of movement distance with which this grade performed short and long patterns (see Table 1). The quality of movement production of grades differed more obtrusively than their performance measures as is reflected by the SNA-ratios of each grade of the six patterns used in Tasks A and B (see Figure 3). As grade one had been practising writing patterns used in these tasks for about six months, they realized writing movements of a relatively high quality. In grade two an impairment of movement production occurred. Although movements gained speed, more spatial variability occurred as well as lower SNA-ratios. Grade three pupils regained a higher quality of writing movements (intermediate SNA-ratios) with less spatial variability.

Effects of Pattern-length

Up and downstrokes of short patterns took 108 ms. more time to realize than up and downstrokes of long patterns ($F(1,29)=14.4$, $p<.001$; $F(1,29)=14.9$, $p<.001$, respectively). No differences existed in the movement distance of the strokes of long and short patterns. Mean and maximum velocities of up and downstrokes were significantly higher for longer patterns (respectively: $F(1,29)=7.5$, $p<.05$; $F(1,29)=38.6$, $p<.001$; $F(1,29)=10.1$, $p<.01$; $F(1,29)=39.4$, $p<.001$). The control subjects performed the short and long writing patterns in a different way. The strokes of short patterns took 42 ms. less movement time than those of long patterns, were 0.4 cm. shorter and realized with lower mean and maximum velocities. These results confirmed our hypothesis concerning the effects of pattern length on the movement characteristics of repetetive writing behaviour. Children, apparently profiting from rehearsal, performed long patterns with faster movement characteristics than short patterns, whereas the reverse was

Table 1 Mean and standard deviations of performance measures per stroke of short and long patterns for grade 1, 2, 3 and control subjects (c).

Task A	short patterns							
grade	movement time (s)		movement distance (cm)		mean velocity (cm/s)		maximum velocity (cm/s)	
	mean	sd	mean	sd	mean	sd	mean	sd
1	.770	.236	1.176	.207	1.678	.568	2.897	.857
2	.742	.232	1.151	.284	1.707	.605	3.032	.602
3	.778	.238	.945	.197	1.314	.373	2.456	.645
c	.213	.054	.825	.154	4.040	.806	8.207	1.841
Task B	long patterns							
1	.657	.163	1.208	.269	1.946	.582	3.628	1.052
2	.676	.203	1.116	.292	1.795	.706	3.566	1.186
3	.632	.145	.899	.240	1.521	.574	3.062	1.026
c	.255	.031	.922	.139	3.330	.554	7.940	1.060

Figure 3 Signal-to-noise amplitude ratios of the copying performance of six patterns used in Tasks A and B for separate grades. Pattern numbers correspond to the text.

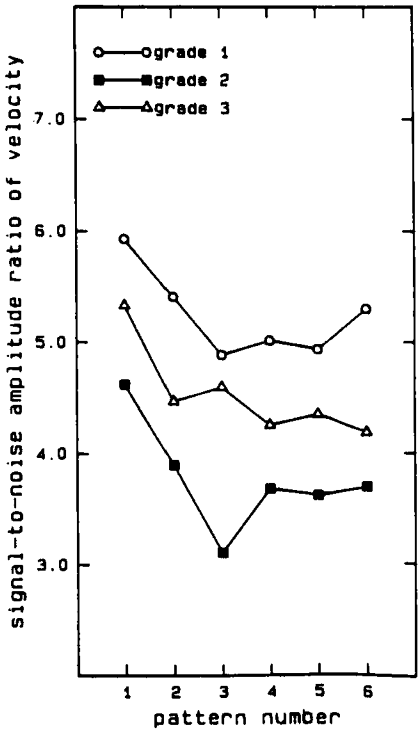


Figure 4 Movement time (upper-left panel), movement distance (upper-right panel), mean velocity (lower left panel) and maximum velocity (lower-right panel) of upstrokes (open circles) and downstrokes (closed circles) of the copying performance of the six patterns in Tasks A and B.

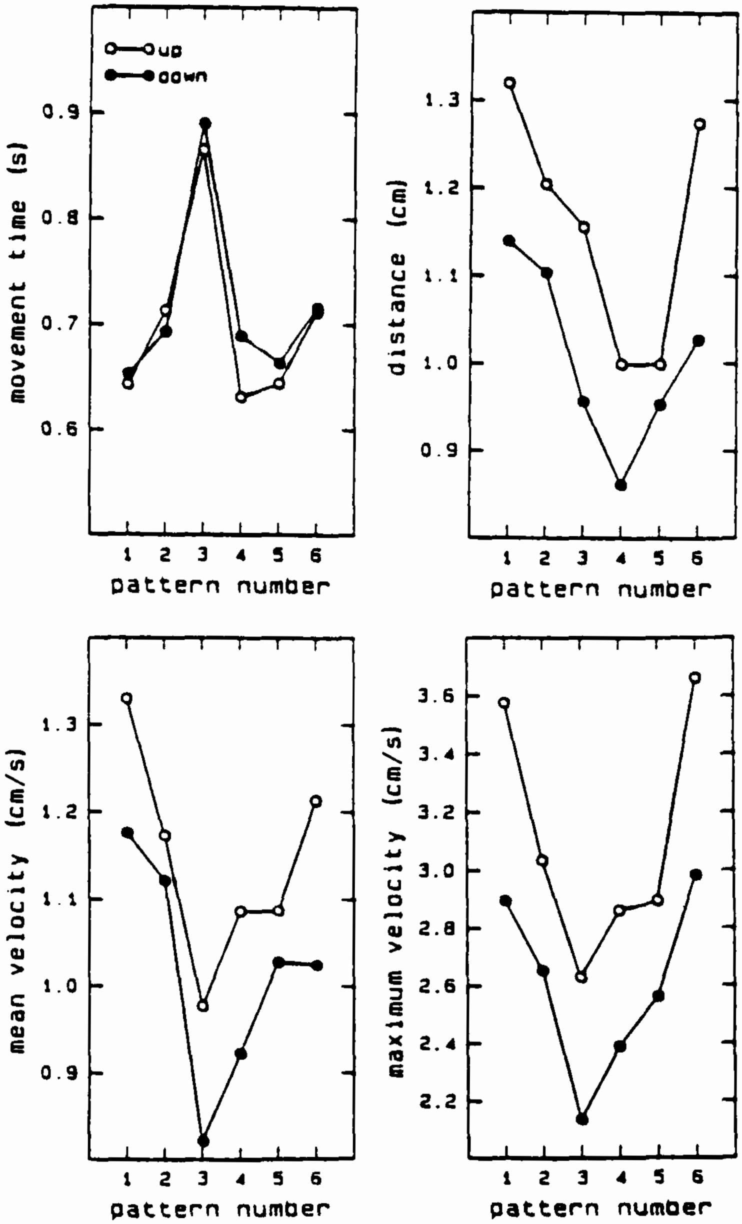
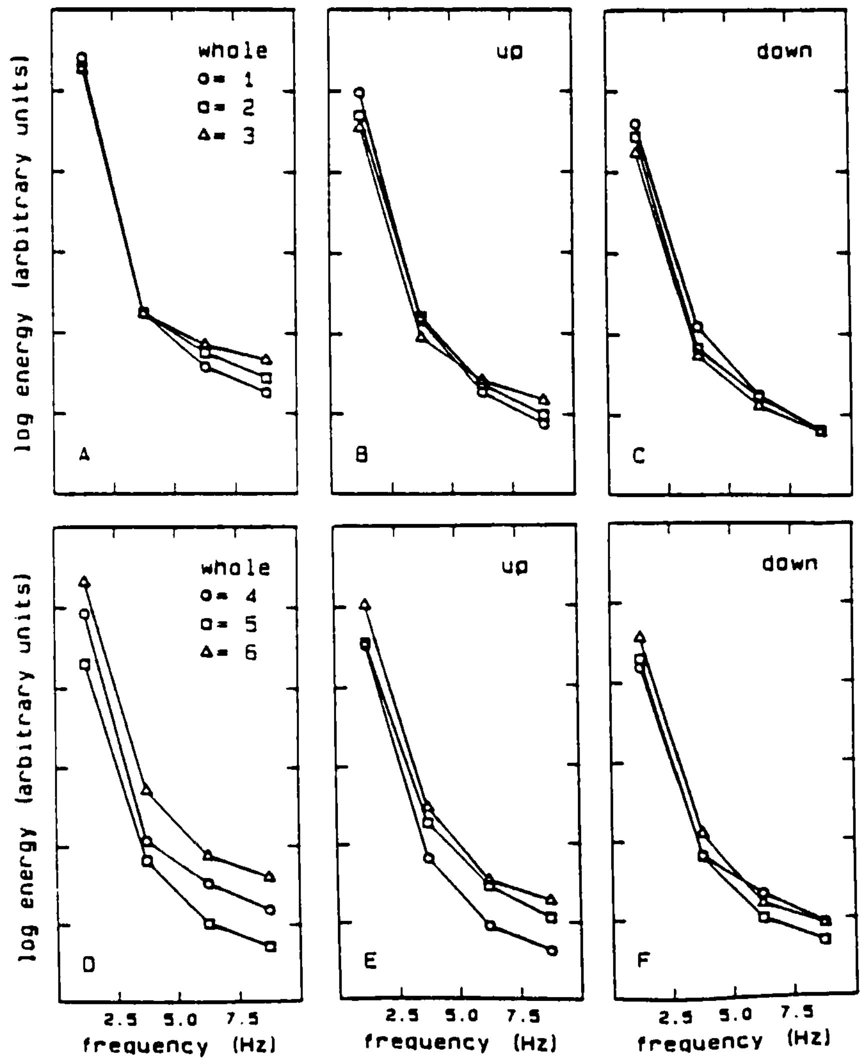


Figure 5 Energy distributions in four equal frequency bands of the copying performance of continuous patterns (upper panels) and discontinous patterns (lower panels) calculated from the absolute velocity data of the whole pattern (left panels), upstrokes (middle panels) and downstroke (right panels). Circles represent anti-clockwise turning patterns (pattern numbers 1 and 4), squares represaent clockwise turning patterns (2 and 5) and triangles represent the patterns with mixed turning directions (3 and 6).



observed in our adult control subjects. The mean SNA-ratios of short and long patterns copied by children were respectively 3.68 and 4.78, reflecting a higher quality of movement production for long patterns as well.

Effects of Degree of Continuity

Degree of continuity had a significant effect on three of the dependent variables. Movement time for continuous patterns (1, 2 & 3) was longer (.067 s.; $F(1,29)=20.7$, $p<.01$), stroke distance was longer (0.25 cm.; $F(1,29)=43.5$, $p<.001$) and mean velocity was higher (0.08 cm/s; $F(1,29)=6.0$, $p<.05$) (see Figure 4). These results do not fully confirm our hypothesis: although continuous patterns took more time per stroke, their trajectories were longer and their mean velocity was higher. With regard to the quality of stroke production, however, the results confirmed our hypothesis. When we consider the discontinuous patterns 4 and 5 (Figure 5, lower panels) it can be observed that the distribution of energy along the spectrum is different for up and downstrokes. The spectrum of the velocity data for upstrokes of pattern 5 has relatively more energy in the high frequency band than of pattern 4. For the downstrokes data the outcome is the reverse. When we consider these two writing patterns we can observe in the corresponding spectra of up-as well as of downstrokes that those strokes which end with an acute angle are less represented in the high frequency band than the continuously changing strokes. It seems that continuous writing patterns are performed with more high frequency movements than discontinuous writing patterns.

The data of Figure 4 also show a fairly constant difference between up and downstrokes. In general upstrokes travel over a longer distance, reach higher mean and maximum velocities and cost less movement time. When we consider that in writing tasks young children realize upstrokes predominantly through abduction of the more proximal wrist and downstrokes through flexion of the more distal fingers, the better performance of the upstrokes may reflect the greater mastery of the proximal musculature of the young child.

Effects of Direction of Rotation

There was a significant effect of direction of rotation on movement time ($F(2,58)=36.1$, $p<.001$), mean velocity ($F(2,58)=17.2$, $p<.001$) and maximum velocity ($F(2,58)=4.3$, $p<.05$). The effect was mainly to be attributed to pattern 3 (.88 s/stroke) which has alternating directions of rotation (see Figure 4). The means of the anti-clockwise patterns (1 & 4) and the clockwise patterns (2 & 5) did not differ significantly (means: 0.654 s/stroke and 0.678 s/stroke respectively). The results partly confirmed our hypothesis concerning the effects of direction of rotation on performance measures of repetetive writing behaviour. Only for continuous patterns writing performance slowed down when the direction of rotation of the writing pattern changed from anti-clockwise to clockwise to an alternation of these two (see Figure 4). These effects were not so clearly present in the data of the discontinuous patterns.

Figure 5 (upper panels) depicts the effects of direction of rotation on the amount of energy in the writing behaviour of our subjects. Direction of rotation of the writing patterns differentially influenced the amount of energy of low and high movement frequencies. As the direction of rotation of continuous patterns (Figure 5, upper panel) changes from anti-clockwise (Figure 5A circles) to clockwise (Figure 5A squares) to an alternation of these two (Figure 5A triangles) the amount of energy of high movement frequencies increased and of low movement frequencies decreased (Figure 5A, $F(3,78)=4.98$, $p<0.001$). This interaction occurred predominantly in the upstrokes (Figure 5B, $F(3,87)=3.99$, $p<0.05$). This means that this change of direction of rotation of strokes corresponded with a gradual impairment of the quality of the writing movements (see Figure 3). These effects of direction of rotation on the quality of stroke production correspond to the hypothesis stated in the introduction.

Task C

Grade Effects

There was no main effect of grade on performances in Task C. Only for the maximum velocity data the interaction of grade and direction of rotation was significant ($F(9,29)=2.3$, $p<.05$). Closer inspection of the data learned that the effect was to be attributed to the upstrokes. While grade one children made no difference between maximum velocities in upstrokes within clockwise and anti-clockwise patterns, grade two and three children realized 13.0% and 15.8% respectively lower maximum velocities in upstrokes of clockwise patterns than in upstrokes of anti-clockwise patterns ($F(9,29)=1.95$, $p<0.10$). Probably because of the effect of more practise of grade two and three children in cursive writing, in which anti-clockwise rotations are dominant (Thomassen and Teulings, 1979), these children realized this direction of rotation with higher maximum velocities.

Effects of Size, Speed-accuracy and Lineature Instructions

An increase in movement distance of strokes of 68.3% as a result of size instructions resulted in increases of movement time (22.7%), mean velocity (39.4%) and maximum velocity (44.2%), all statistically significant. Speed instructions decreased the mean movement time of strokes with 31% ($F(1,29)=98.74$, $p<0.001$), their distance with 5% ($F(1,29)=6.22$, $p<0.001$) and resulted in an increase of the mean and maximum velocity per stroke of respectively 38.5% ($F(1,29)=80.62$, $p<0.001$) and 28.9% ($F(1,29)=57.52$, $p<0.001$).

The presence of a height constraint increased the movement time of upstrokes with 19.7% ($F(1,29)=36.69$, $p<0.001$), their movement distance with 19.2% ($F(1,29)=28.27$, $p<0.001$). The effect was not restricted to upstrokes. Downstrokes increased 17.3% in movement time ($F(1,29)=37.28$, $p<0.001$) and 15.8% in movement distance as a result of this constraint ($F(1,29)=31.56$, $p<0.001$).

The results of the control subjects were quite different. An increase in movement distance of 69.4% as a result of size instructions was realized in only 6.4% more movement time, (whereas children needed 22.7% more writing time) and with 49.4% and 54.5% higher mean and maximum velocities respectively. A larger writing size hardly influenced the writing time of the adult control subjects. They performed larger writing sizes with higher maximum velocities and corresponing higher force amplitudes. In children larger sizes were only partly realized with higher force amplitudes but with significantly longer writing times. Speed instructions decreased the movement time of strokes of the control subjects with 56.6%, their distance with 4.9% and increased mean and maximum velocity with 61.8% and 55.0% respectively. They increased force amplitudes more in adult's writing than in children's writing but in both were realized with higher maximum velocities. A height constraint increased the movement time of upstrokes with 14.8% ,their movement distance with 38.9% and decreased mean and maximum velocity with 22.5% and 17.9% respectively. The movement time of downstrokes increased with 33.2%, their distance with 47.9%, while 23.6% and 31.0% lower mean and maximum velocities were realized in the presence of this constraint. While in children the movement characteristics of up and downstrokes were almost equally effected by the presence of a height constraint, in adults downstrokes were more effected than upstrokes. In the latter case the prolonged movement time for downstrokes probably reflects programming activity for the correct realization of the height constraint of the upcoming upstroke.

Interactions

In absence of a height constraint the children performed the upstrokes of large patterns with 14.2% more movement time than the upstrokes of small patterns, whereas in the presence of a height constraint this difference increased to 31.7% ($F(1,28)=16.23$, $p<0.001$). The same interaction occurred in the movement time of downstrokes (respectively: 17.1% and 28.8% increments in respectively absence or presence of a height constraint; $F(1,28)=23.42$, $p<0.001$). Size instructions had a slowing down effect on writing performance when a height constraint was present. When present, a height constraint elicited a 16.8% extra difference in movement distance between upstrokes of large and small patterns ($F(1,28)=13.91$, $p<0.01$) and a 17.1% extra difference in movement distance between downstrokes of large and small patterns ($F(1,28)=18.72$, $p<0.001$). This means that a height constraint took longer time to realize in the case of of large writing patterns. A different effect was observed when speed and size instructions were combined. Under accuracy instructions upstrokes of large patterns were realized with 35.3% higher mean velocity than upstrokes of small patterns, whereas under speed instructions this difference increased to 43.0% ($F(1,29)=14.05$, $p<0.01$). For downstrokes these percentages were respectively 36.7% and 40.1% ($F(1,29)=15.75$, $p<0.001$). A combination of speed and size instructions fastened up writing performance. Figure 6 depicts a positive interaction between speed-accuracy and lineature instructions. In both absence and presence of a height constraint speed instructions decreased the movement time of up and downstrokes with 31%. Without a height constraint speed instructions resulted in 8.9% shorter upstrokes and 7.8% shorter downstrokes whereas with a height constraint speed instructions resulted in only 2.2% shorter upstrokes and 2.0% shorter downstrokes (upstrokes: $F(1,28)=5.44$, $p<0.05$; downstrokes: $F(1,28)=3.70$, $p<0.10$). The mean velocity of upstrokes without a height contraint increased 30.7% and with a height constraint 45.2% as a result of speed instructions ($F(1,28)=4.02$, $p<0.10$). The same interaction occurred in downstrokes where a 33.8% and a 42.4% increase in mean velocity was observed as a result of speed instructions in the absence and presence of a height constraint respectively ($F(1,28)=5.56$, $p<0.05$). Speed instructions in the presence of a height constraint fastened up writing performance more than in the absence of a height constraint. This interaction showed that a combination of speed instructions and a height constraint resulted in a significantly faster writing performance.

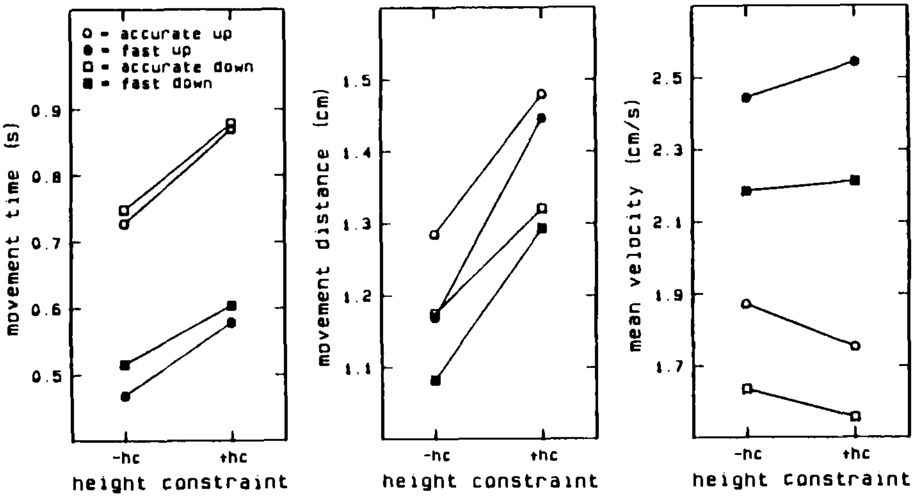
Effects on the Amount of Energy in Different Movement Frequencies

The effects of direction of rotation of the two patterns used in Task C were identical to those observed in Tasks A and B. The clockwise writing pattern elicited relatively more energy in higher than in lower movement frequencies as compared with the effects of the anti-clockwise writing pattern. Speed instructions increased the energy of movement frequencies between 2.5 Hz and 7.5 Hz ($F(1,27)=17.78$, $p<.001$). The mean SNA-ratio of accurately produced writing movements was 4.76 whereas this ratio increased to 5.18 as a result of speed instructions. Speed instructions improved the quality of stroke production. Size instructions differentially increased the energy in lower (0-2.5 Hz) and higher (7.5-10 Hz) frequencies ($F(3,81)=8.54$, $p<.001$), the mean SNA-ratio of larger sizes being somewhat higher (5.29) than the mean SNA-ratio of smaller sizes (4.76). A similar, but smaller, effect was observed with regard to the presence of a height constraint ($F(3,78)=2.25$, $p<.10$). The mean SNA-ratio of writing movements increased from 4.92 to 5.01 in the absence and presence of a height constraint respectively.

Interactions

In the absence of a height constraint the mean SNA-ratio decreased from 4.94 under accuracy instructions to 4.91 under speed instructions, whereas in the presence of a height constraint an increase from 4.57 to 5.51 was

Figure 6 Movement time (left panel), movement distance (middle panel) and mean velocity (right panel) of upstrokes (circles) and downstrokes (squares) in the absence or presnece of a height constraint (X-axis) and under accuracy (open markers) and speed-instructions (closed markers).

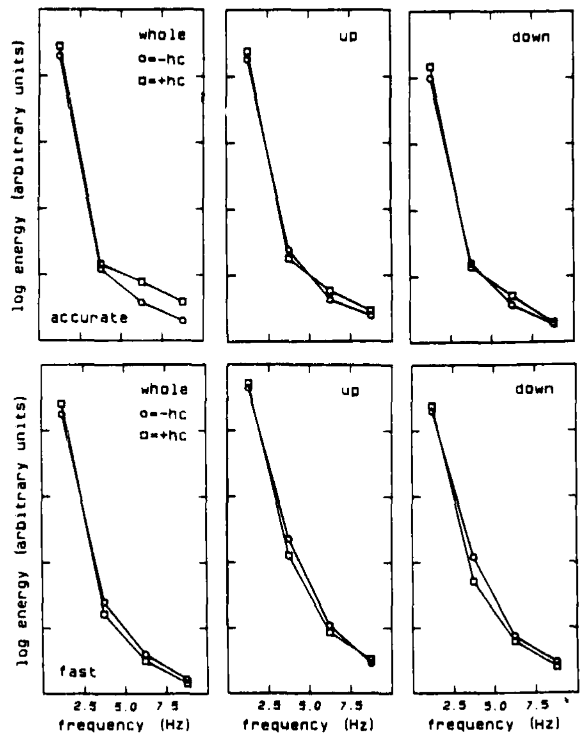


observed as a result of speed instructions (Figure 7, upper panel; $F(3,73)=2.63$, $p<.10$). A height constraint combined with accuracy instructions elicited a slowing down of writing performance and an impairment of the quality of movement production. A similar interaction was observed between height constraint and size instructions. When a height constraint was absent large patterns elicited more energy in high movement frequencies ($F(3,78)=2.19$, $p<.10$) than in the presence of a height constraint (SNA-ratios being respectively 5.39 and 5.17). Practising instructions which elicited faster writing performances (size and speed instructions) also elicited a higher quality of movement production when an upperline as height constraint was present. Our assumption was that this upperline would elicit preprogramming of spatial goal positions which is a characteristic of a more ballistic movement strategy. An improvement of the quality of stroke production also occurred when large patterns had to be written and speed instructions were given. Speed instructions reduced the amount of energy of high frequencies in the case of large patterns ($F(3,81)=2.78$, $p<.05$) resulting in higher SNA-ratios (respectively 5.11 to 5.74).

DISCUSSION

Analysis of differences in writing performances between first, second and third grade primary school children brought up evidence for a non-monotonic development of performance. A possible explanation for this finding may be found in a developmental model analogue to the model of Hay (1979,

Figure 7 Energy distributions in four equal frequency bands of the copying performance in Task C under accuracy instructions (upper panels) or speed instructions (lower panels) and under the absence (circles) or presence (squares) of a height constraint calculated from the absolute velocity data of the whole pattern (left panels), upstrokes (middle panels) and downstrokes (right panels).



1984) and Von Hofsten (1979, 1980): first grade children follow a ballistic strategy, second grade children write faster but with many corrections and third grade children show a regain of control of a more ballistic strategy in their writing performance.

The pattern length effects we found with children differed with those found with our adult control subjects. It may be concluded that children profit from rehearsal and follow a more piecemeal strategy in the production of strokes. Long writing patterns lead to the investment of more effort than short writing patterns, resulting in a faster writing performance. Adults, however, perceive and perform the task as a whole (Thomassen & Teulings, 1983). For them longer patterns lead to more complex retrieval and unpacking processes (Sternberg, et al., 1978) than shorter ones, resulting in a slower writing performance in the former.

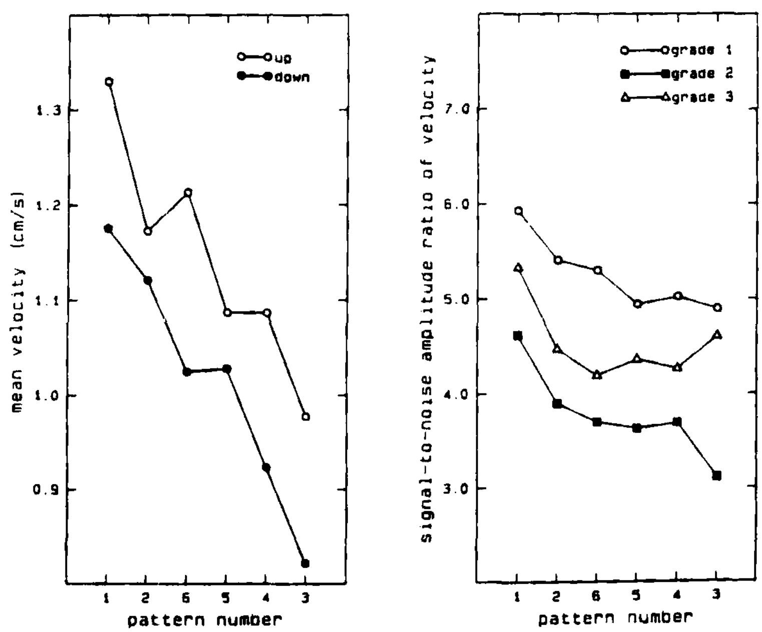
Continuous writing patterns, without acute angles, were performed in a higher speed than discontinuous writing patterns. It could be that writing with discrete stops at a stroke transition point entails the specific difficulty of preparing that stop during the execution of the ongoing stroke. Hulstijn and Van Galen (1983) have presented evidence that writing short sequences of strokes with discrete stops lead to longer reaction times than would be expected from the limited length of the sequence itself. Thus preparing a stop could have counterbalanced the higher complexity of continuous writing patterns. Although movements were faster in the case of continuous writing patterns, the quality of the writing performance as expressed in the SNA-ratios was worse. The quality of stroke production of discontinuous writing patterns is higher than of continuous writing patterns. A possible explanation for this finding might be that the co-articulation that is needed for a continuous transition between up and downstrokes is not yet an automatised process at the age levels of our subjects and place an extra demand upon writing performance. The analysis of the spectrum of the velocity data confirmed the view that continuous transitions ask for more coordination and entail more movement instability: trajectories connecting upstrokes with downstrokes along an i.e., continuous, curve (Figure 1, pattern 5) had more energy in the high frequency band than comparable trajectories that end in sharp transition points (Figure 1, pattern 4).

The direction of rotation of continuous repetetive writing patterns influenced performance measures and the quality of stroke production as predicted. Anti-clockwise rotating writing patterns without acute angles were written in the highest speed and with a relatively high quality. Clockwise rotating writing patterns were performed more slowly and with less quality and the writing pattern with alternating directions of rotation seemed to be the most difficult writing pattern for children. With regard to the discontinuous writing patterns the effects of direction of rotation were not as predicted. It seems that the presence of acute angles within repetetive writing patterns overrule the effects of the complexity variable direction of rotation.

Our data show a substantial and systematic difference between up and downstrokes. We suggested that the more proximally performed upstrokes are easier to realize because fewer muscular systems have to be coordinated as compared to the joint flexion of the distal parts of the fingers which is necessary for the downstrokes (Meulenbroek, et al., 1985). This finding has also been reported for adult subjects with letter writing tasks (Van Galen & Teulings, 1983) and with line drawing (Van Galen & Teulings, in prep.).

An unsolved problem for motor theory is the definition of structural complexity of movement patterns. Keele (1981) has proposed an alternative view on structural complexity which corresponds with the results of our experiment. Based on Hollerbach's (1978) theory that the form of cursive writing patterns is established by the phase relations of the two orthogonal sets of muscles, superimposed on a left-to-right background movement, and assuming that the basic elements of a pattern are defined by the points within that pattern where a new phase relation is set between those muscle sets, one could order the writing patterns of our experiment in a different manner. Pattern 1, 2 and 6 all are characterized by a simple and constant phase relation between the X and the Y-dimension. In patterns 4 and 5 a change in phase relation occurs after each completion of an arcade and for pattern 3 the phase relation is reversed every time the pen passes a point halfway an up or downstroke. In Figure 8 (left panel) we have rearranged the six patterns according to this view, and pitted against their mean velocity. It might be clear that a very consistent ordering of the patterns has been acquired. The data on the signal-to-noise amplitude ratios (Figure 8, right panel) are nicely in agreement with the hypothesis that the number of phase transition points per trajectory defines the motoric complexity of a pattern.

Figure 8 Rearrangement of pattern order for the mean velocity data (left panel) and signal-to-noise amplitude ratios (right panel) of Tasks A and B according to increasing pattern-complexity defined by increasing number of phase transition points per pattern.



With regard to the effects of various instructions on the copying performance the results of the experiment showed that certain combinations of instruction lead to higher qualities of movement production. Children tend to realize larger writing patterns by changing the temporal patterning of their performance instead of using higher force amplitudes and corresponding higher mean and maximum velocities. The effects of speed instructions showed that children were able to use this latter strategy, which is characteristic for adult writing, fairly well. Speed instructions considerably increased mean and maximum velocity of writing performance and resulted in a higher quality of stroke production. The effects of a height constraint showed that children perform repetetive writing patterns stroke by stroke. The childrens' performance measures of upand downstrokes were equally effected by the presence of an upperline whereas with the adult control subjects donwstrokes were more effected than upstrokes. We interpreted this latter result as reflecting programming activity for the correct realization of the height constaint of the upcoming upstroke. When larger sizes had to be written speed instructions improved the quality of stroke production probably because the children were forced to use higher force amplitudes instead of changing the temporal patterning of their performance. The combination of a constraint on writing height and speed instructions might have elicited a more ballistic strategy in performance because it forced the children to plan in advance spatial goal positions (Pantina, 1957).

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Graphonomics: Contemporary Research in Handwriting
H.S.R. Kao, G.P. van Galen, R. Hoosain (eds.)

AN ANALYSIS OF CHILDREN'S PENHOLDS

Rosemary Sassoon[1]
Ian Nimmo-Smith
Alan M. Wing

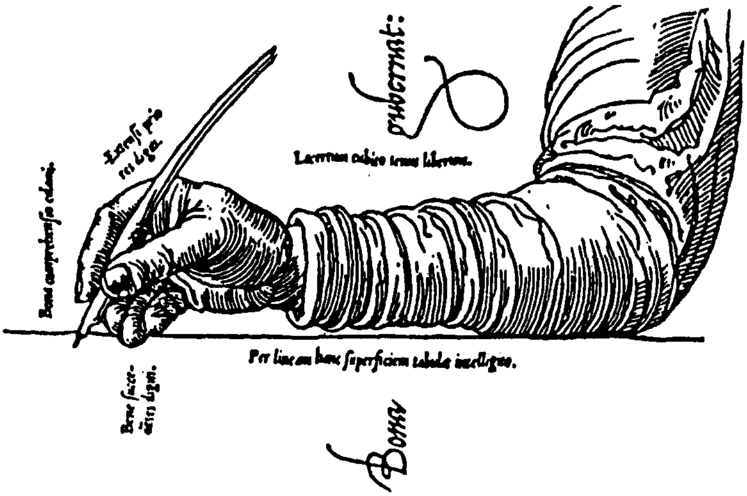
INTRODUCTION

Historical Background

Writing masters have long stressed the connection between the way the writing implement is held and the resulting strokes of the pen. Thus, for example, Lucas (1571) described four errors "particularly damaging to anyone who embodies them in his penhold." These errors related to the positioning of the arm and to the use of the fingers and thumb in supporting and moving the pen. We may presume the damage referred to by Lucas involved factors such as quality of line and consistency of letter form.

As letterform models and writing tools changed so did penholds. Writing masters gave detailed descriptions of both finger and hand positions to ensure optimum penhold to achieve desired letterforms with specific writing implements. For example, Mercator (1540), using a square-cut quill to achieve italic letterforms (chancery script), advised (see Figure 1) a penhold with the hand on edge, thumb and finger (interphalangeal) joints extended and any weight of the hand not taken by the elbow "supported only on the little finger, with the least possible pressure, thereby enabling the hand to move readily in any direction." This description suggests writing was accomplished largely by movement of the whole hand rather than by finger movement. Gordon (undated, 19th century) gives rather different instructions for writing copperplate letterforms using a flexible, fine-pointed metal nib. He observed that "ragged edges will be produced if the hand is allowed to rest on the side" and suggested "the wrist should be kept nearly flat." Instead of an extended thumb he stated it should be flexed with "the nail in fact almost, or quite, touching the pen, with the thumb as much under the pen as possible." Letter formation was the result of thumb and finger action.

Figure 1 Penhold advocated by Mercator (1540).



In Britain there is at present no uniform policy for teaching handwriting in schools. Letterform models in use range from italic to cursives derived from copperplate. Modern writing implements used in schools often differ considerably from the pens for which the models were originally designed. Unlike nibbed pens, for example, the modern ball-point pen, produces a written trace of uniform line thickness, with little constraint on direction of movement of the pen point. However, the ball-point does require the pen to be held relatively upright. There is, in general, less emphasis on handwriting appearance, provided the writing is legible. Speed has become an important factor. If, as seems reasonable, writing is a product of letter forms, writing implement and penhold, the current lack of educational emphasis on the process of writing may be expected to be of some consequence.

Working in an educational context, one of us (RS) has observed a variety of penholds used by children when writing. Even casual observation reveals that some of these penholds deviate quite markedly from what is usually termed the dynamic tripod (e.g., Elliott and Connolly, 1984) where the pen is supported by the tips of the thumb, index and middle finger plus the web between the thumb and index finger. Does deviation from the dynamic tripod have an effect on the process of writing? Is the dynamic tripod, so favoured by teachers, the most efficient for all children? Is it perhaps more appropriate to the fountain pen than to the ball-point pen since the latter requires the pen barrel to be held more upright? However, before questioning the various penholds in these terms information is needed about the range of penholds currently employed by school children.

Classification of Penholds

Although prescriptions for how to hold a pen may be found in the numerous books on handwriting instruction, we know of only one published study of penholds actually used by schoolchildren. In a survey of Australian children aged between 6 and 14 years, Ziviani (1983) recorded the presence or absence of four aspects of penhold based on the presence or absence of four features. The features were: flexed proximal interphalangeal joint of the index finger, pronated forearm, more than thumb and finger on the pen barrel, opposed thumb and finger. Ziviani claimed that her data revealed clear developmental trends in the nature of the penhold. In particular she stated that the proximal interphalangeal joint of the index finger was more likely to be strongly flexed in younger children and that they were more likely to pronate the forearm. Unfortunately, Ziviani's presentation of the proportion of children displaying a given feature was unadjusted for their age distribution so that the claimed age related changes in grip must be treated with caution.

In the present paper we report a study of changes in penhold as a function of age in English schoolchildren between the ages of 7 and 16 years. Penholds are described in more detail than in the Ziviani study using a refinement of Jacobson and Sperling's (1976) approach to classifying hand-grips used in holding a variety of objects. As an index of changes in writing ability we present data on writing speed and relate it to penhold.

Our classification scheme is summarised in Table 1.

Table 1 Penhold classification summary.

Feature	Values	
DIGITS		
Contact with pen	1: On barrel	2: Not on (or below, if finger)
Position on pen	1: Side	2: Top
	3: Half over	4: Right over
Proximity to pen tip	1: Nearest	2: Equal nearest
	3: Second	4: Equal second
	5: Third	6: Fourth
Shape of digit	1: Ext; ext	2: Hypext; flex
(distal; proximal)	3: Flex; flex	4: Ext; flex
	5: Tucked in	
HAND		
Rotation	1: Slightly flattened	2: On edge
UPPER BODY		
Upper body posture	1: Upright	2: Body left; head right
	3: Bent left	4: Bent over top
	5: Bent right	6: Sits sideways
PAPER		
Orientation (re shoulder line)	1: Anticlockwise	2: Square
	3: Clockwise	
Position (re body midline)	1: Left	2: Centre
	3: Right	

Each of the five digits is first classed as to whether it touches the side or top of the pen barrel or if it is below or not in contact with the pen. Provided the digit is touching, the next three descriptors are scored. The second descriptor indicates where on the pen the digit makes contact. Defining top of the pen as the uppermost surface, the possible values for this descriptor are touching side, touching top, half-over the top (touching side and top), right-over (touching top and two sides). A third descriptor is relative proximity of the tip of the digit to the pen tip and this is determined as nearest, equal nearest, second nearest, second equal, third, fourth.

A fourth descriptor for each digit refers to the angle of the interphalangeal joints. The first category is for the distal and proximal interphalangeal joints extended so that the three phalanges lie roughly in a straight line. If the distal interphalangeal joint is hyperextended so that the joint appears to be bent the wrong way (and this implies flexion of the more proximal interphalangeal joint) the second category is scored. A third category is for distal and proximal joints both flexed. A fourth category is distal extended, proximal flexed. The final category observed is for cases in which the digit is tightly "curled up." Some illustrative penholds, redrawn from photographs, are shown in Figures 2 and 3.

Postural Description

While the focus of the present paper is on the description of penhold, the posture of the writer, including factors such as arm position, wrist angle, paper position, must also have an influence on writing. As a preliminary to further work we have therefore observed whether the forearm is pronated such that the hand appears either somewhat flattened or on edge. We note the angle of the wrist. Upper body posture is described in terms of any tendency to lean the head or body one way or the other with respect to the vertical. Also classified is the position of the paper, in relation to the midline of the body (centred, left, right), and its orientation.

Figure 2 Penhold examples (redrawn from original photographs) showing digit position on pen:
(1) Thumb and index both on side
(2) Thumb and index both on top
(3) Thumb half over
(4) Thumb right over

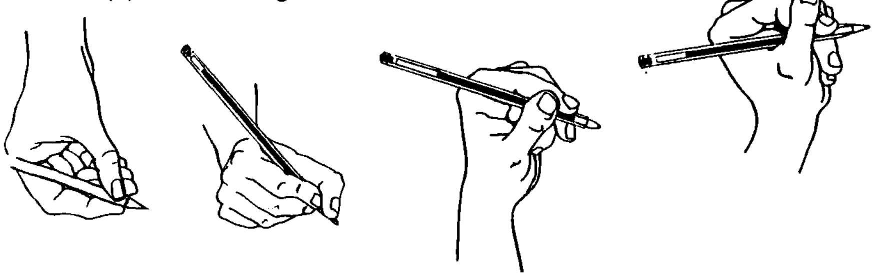
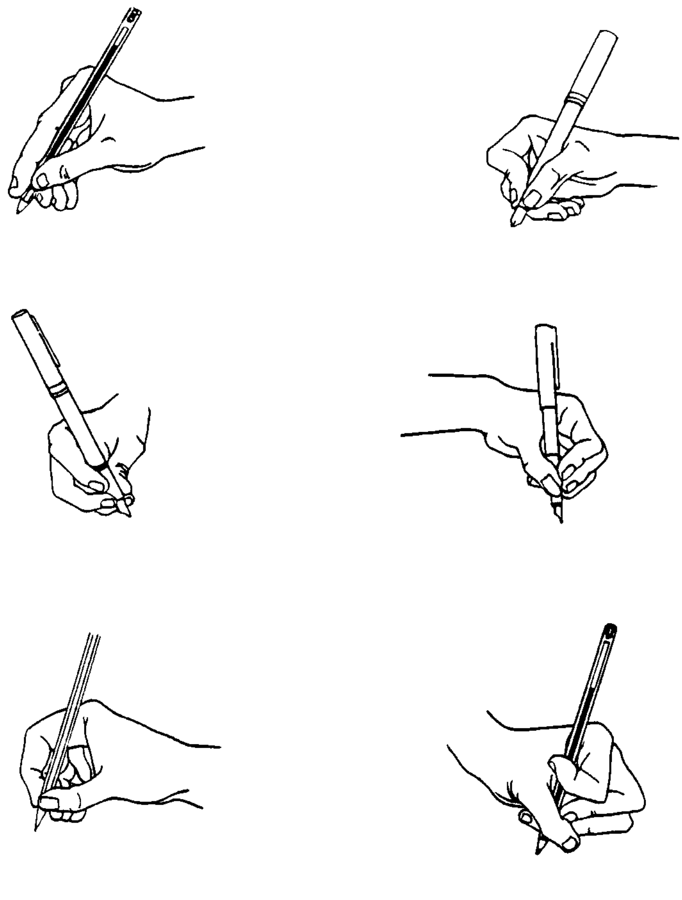


Figure 3 Penhold examples showing a variety of digit shapes
Left side:
(1) Thumb and index finger both ext; ext
(2) Thumb hyperext; flex
(3) Index finger flex; flex
Right side:
(4) Index finger hyperext; flex
(5) Index finger ext; flex
(6) Index finger curled up



Figures 2 and 3 reproduced by permission of Arnold Wheaton.

THE SURVEY

Subjects

The handwriting of children from three age group was sampled[2]. The first group comprised 91 children (average age 7y 6m, SD 4m; 17 left-handed for writing) in their first year (following two years of primary education) at five state and one private junior schools in Kent. All had mastered the use of at least pencils and ball-point pens in printing all the letters of the alphabet. With the exception of the private school children, they had not received class instruction in joining letters. The second group were 100 nine year-olds (average age 9y 6m, SD 4m; 10 left-handed for writing) in the third form of the same junior schools as the first group. They had all received some instruction in joining letters. However, handwriting instruction at two of the schools was based on italic model with little emphasis on joining letters. The other four schools taught cursive writing from differing models. The third group of 103 children (average age 15y 8m, SD 3m; 16 left-handed for writing) were in their fourth year (the last year of compulsory schooling) in two separate secondary schools in the same geographic area as the first two groups. There was no class instruction of handwriting in the secondary schools.

Assessment Procedure

Each child was tested individually by the first author (RS) in a session lasting 10 to 15 minutes. The child was seated at a school table with a horizontal surface. A black ball-point was supplied for writing. The paper used was wide (8mm)-ruled A4 which the child was allowed to position at a comfortable orientation. After writing his or her name, the child wrote out three different sentences presented on typed cards. The time taken to write each sentence was noted. To reduce unreliability in timing due to hesitations associated with spelling uncertainties, etc., practice was given with the first two sentences by having the children write them out once (15 year olds) or twice (7 and 9 year olds) before timing them. This was not necessary for the last sentence which was based on a familiar nursery rhyme. The first two sentences were to be written at normal speed (i.e., without specific speed instructions), the third as rapidly as possible two sets of sentences were used: one set (lengths 8, 9 and 7 words) for the seven and nine year olds; the other set (lengths 9, 13 and 8 words) for the secondary school children[3].

While the child was writing, usually during the second sentence, at least two photographs were taken from a point above and slightly in front of the child. These were used later to classify the nature of the penhold.

RESULTS

The Modal Category

The results of the classification of penhold are presented for the most part in terms of the modal category for each feature. The modal category is the most frequently occurring category of a mutually exclusive set of alternatives. Thus for example, Table 2, shows the frequencies of occurrence of the different categories of upper body posture. The modal category over all children is seen from the last column to be upright, and this also happens to be true of the different subgroups of children except for the left-handed 9 year olds.

Table 2 Frequencies of occurrence of different upper body postures.

Preferred hand:	Right			Left			
Age:	7	9	15	7	9	15	
Posture							
Upright	41	51	68	11	2	13	186
B Left; H Right	1	4	0	0	0	0	5
Bent left	28	26	8	0	0	0	62
Overtop	4	1	7	0	3	1	16
Bent right	0	2	4	6	5	2	19
Sideways	0	6	0	0	0	0	6
	74	90	87	17	10	16	294

Table 3 documents paper orientation and position. In this case the modal categories are different for right and left-handers. Right-handers most often place the paper to the right, rotated anticlockwise whereas left-handers tend to place it centrally or to the left, rotated clockwise. Careful inspection shows the difference between leftand right-handers sharpens with age. This age by handedness interaction is statistically significant ($X^2(5)=24.1$, $p<.01$).

The proportion of children with the hand on edge decreases with age from 33%, 25%, 14% for 7, 9 and 15 year olds.

Penholds Described

We now turn to a summary of the modal features of the children's penholds. These are presented in Table 4 as percentages separately for each age group. The modal value for each feature was in all cases constant across age. Of particular interest are two findings that go against the typical pictures in handwriting manuals of the ideal penhold. The table shows that, in the majority of cases, the thumb rather than the index finger is closest to the tip of the pen and that there is usually hyperextension at the distal interphalangeal joint of the index finger.

Table 3 Frequencies of occurrence of different paper positions and orientations.

Preferred hand:	Right			Left			
Age:	7	9	15	7	9	15	
Position							
1 Left	1	0	6	8	4	8	27
2 Centre	29	15	6	8	6	7	71
3 Right	44	75	75	1	0	1	196
Orientation							
1 AntiCW	35	78	83	0	2	2	200
2 Square	38	12	4	9	2	1	66
3 CW	1	0	0	8	6	13	28

Table 4 Modal penhold feature values and percentage of children at each age exhibiting modal value.

Feature	Modal value	Age group 7	9	15
THUMB				
Contact	1: On barrel	100	100	100
Position	1: Side	55	61	61
Proximity	1: Leading	67	66	62
Shape	3: Flex; flex	86	92	89
INDEX FINGER				
Contact	1: On barrel	100	100	100
Position	1: Side	81	78	67
Proximity	3: Second	35	33	31
Shape	2: hypext; flex	64	62	62
MIDDLE FINGER				
Contact	2: Below/off	71	73	85
RING FINGER				
Contact	2: Below/off	99	98	98
LITTLE FINGER				
Contact	2: Below/off	100	100	100

It can be seen that, in general, the proportion of children in each age group using the modal feature is also very consistent. There are two notable exceptions. The first is that there is a reduction with age in the proportion of children positioning the index finger on the side of the pen; the contrast between the 7 and 9 year olds and the 15 year olds is statistically significant, ($X^2(1)=5.6$, $p<.05$). The second change with age is the decreasing in frequency with which the middle finger touches the pen on the top or side (shown in the table as an increase in contact below or off). The difference between the 7 with 9 year olds and the 15 year olds is again statistically significant, ($X^2(1)=5.0$, $p<.05$). No statistically significant effects of sex or preferred hand on the proportion using the modal feature were observed.

So far we have considered each penhold feature in isolation. However, any one person's penhold is defined by a combination of features. Thus, for example, Elliott and Connolly's 'dynamic tripod' penhold may be described as one in which the thumb and index finger act on opposite sides of the barrel, with the remaining digits below or off. This was observed in only about one third of the children in each age group (see Table 5).

Table 5 Percentage of children exhibiting 2 types of penhold.

Penhold	Age group		
	7	9	15
Dynamic tripod	34	37	38
Modified tripod	71	72	85

Ziviani (1983) suggests that this definition of tripod penhold may be broadened by the addition of those penholds with the middle finger on the barrel, and by relaxing the restriction on the positions of thumb and index finger. This means including penholds where the finger or thumb is on top of the pen rather than on the side. Some three-quarters of the children in our study had penholds satisfying this description of 'modified tripod' penhold. It is interesting to observe the proportion increases with age, the difference between the 7 with 9 year olds and the 15 year olds being statistically significant, ($X^2(1)=5.98$, $p<.05$).

Penhold and Writing Speed

The average writing speed for the first two sentences (written normally) taken together and the third sentence (written as fast as possible) are presented in Table 6 in terms of the number of characters written per minute. From 7 years to 9 years there is an increase in speed of approximately 50%, and from 9 years to 15 years of another 70%. All three age groups were able to speed up by about 25% when asked to write as fast as possible.

Table 6 Writing speed (in characters per minute) as a function of age.

Sentence	Age group 7	9	15
Average of (1) and (2)	46	64	117
(3)	55	82	140

The effects of the various penhold features on writing speed were assessed by comparing the writing speed of those children adopting the modal value of each penhold feature with the writing speed of the other children. In most cases no significant difference was found. The principal exception relates to the relative position of the thumb and index finger on the pen barrel. For 15 year old children, those with the index finger leading (nearer the writing point) wrote significantly faster, both when writing at a normal speed and when writing as fast as possible; for the latter measure, the average was 150 letters per minute against 136 letters per minute ($t(101)=2.28$, $p<.05$).

We found no significant advantage in terms of speed to writing with either the dynamic or modified tripods described in the preceding section. If anything, there was a slight trend in the opposite direction.

DISCUSSION

This study shows that it is possible to describe penholds in a systematic and detailed fashion suitable for quantitative analysis. Our data show two main differences between the penholds actually used by schoolchildren in Britain today and those commonly illustrated in writing manuals. One was that in over 60% of children the distal interphalangeal joint of the index finger was hyperextended. This suggests perhaps that the majority of children hold their pens too tightly. The other was the surprising number of children (65%) who write with their thumbs closest to the pen tip (writing manuals usually suggest that the index finger should lead). Although not formally quantified, we have also observed that the digit nearest to the tip of the pen was usually considerably closer than would normally be recommended by teachers. One consequence of this might be a reduction in visual feedback from the pen trace as it is produced.

The speed values that we report are somewhat faster than those presented by Groff (1961). This probably reflects the different letterform models in use in the two countries and the shorter texts used in the present study. In our study we looked at the ability to write faster on demand, finding similar percentage increases at different ages. This represents a surprisingly large reserve capacity and points to the need for the researcher to give explicit instruction when trying to assess handwriting proficiency in terms of speed.

Despite the large changes in writing speed with age over individuals we only found two points of evolution of grip with age; index finger less often on the side and middle finger less often on top/touching side.

To us, a surprising finding was that there appears to be little cost to adopting an unconventional, i.e., non-modal, penhold feature at least in terms of speed of writing. However, of course writing speed should not be the only criterion; legibility is clearly likely to be at issue. Thus work is at present in hand to examine the effects of non-modal penholds on letter formation.

One implication of the relative lack of effect of penhold, at least on writing speed, is that a child writing with an unconventional penhold would not necessarily do better to adopt a more conventional grip. In this context it is interesting to note Otto, et al's (1966) study showing that adults are able to adopt a modified grip with the pen lying between the index and middle fingers with little difficulty. In our study only one child, a 9 year old girl, had spontaneously adopted this penhold. After assessment this penhold was tried out with those secondary school pupils who complained of pain while writing. On the whole they found that it helped considerably. This way of holding a pen can also prove helpful in certain neurological conditions, for example, where it may be unsatisfactory for someone to adopt a dynamic tripod.

One aspect of penhold that we have not classified upto now but which we feel deserves examination is where on the hand is the highest point of contact with the pen. While many modern instruction manuals would advocate the web between the index finger and thumb we have often observed it lying closer toward the proximal interphalangeal joint of the index finger which causes the pen to be held more upright.

In the present study we have only described the way the pen is held and have not attempted to document the dynamics of the writing movements. A method of analysing the contribution of finger, wrist or arm movements to movement of the pen-point is outlined in the Appendix. With this approach it will be possible in future work to ask whether two children with the same penhold are using the same movements of the upper limb to drive the pen. Certainly, it is our impression that some children adopt a penhold that conforms to a dynamic tripod but use movements of the whole arm rather than of the fingers to drive the pen. One need only turn to the pioneering work of Woodworth (1899) to appreciate that this should have consequences both for the form of the letters produced and for the speed.

FOOTNOTES

1. Presentation of this paper was made possible by a British Council Grant to RS.

2. We are grateful to the children, teachers and Education Committee of Kent County Council for participation, assistance and permission in undertaking this study.
3. Copies of the text written by the children may be obtained from the first author.

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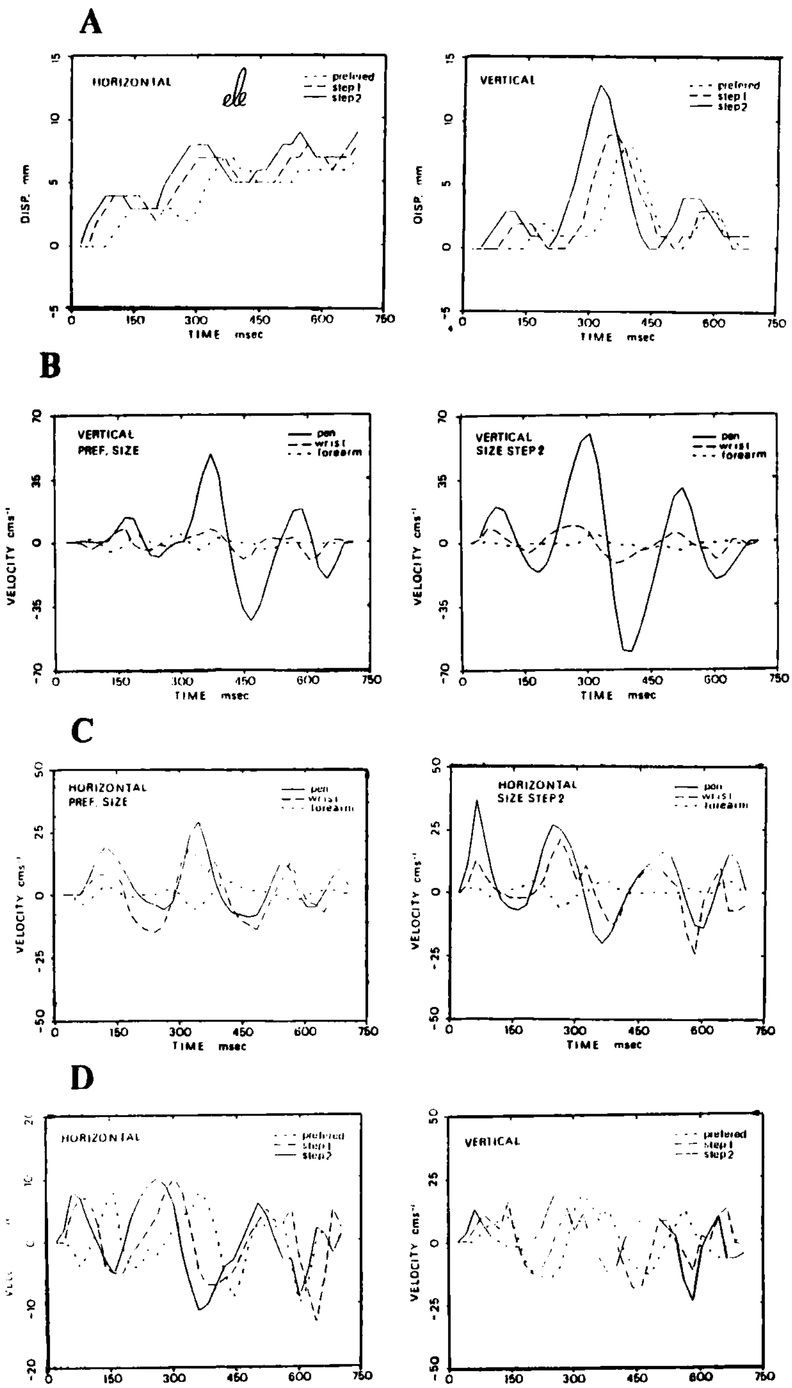
APPENDIX

Appraising the Relative Contributions of Hand, Wrist and Forearm to Movements of the Pentip by John P. Wann, MRC Applied Psychology Unit, England

Different penholds may place varying degrees of limitation on movement of the fingers. Correspondingly, different relative contributions of the other skeletal links in the upper limb, namely the hand and forearm, may be required to effect a given pen movement. It is also conceivable that different writers employing the same penhold could drive the pen with different relative contributions of the skeletal links of the upper limb. With the focus for research suggested by the body of this paper on possible relations between penhold and writing behaviour, it is worth noting objective measurement of the relative contributions of finger, hand and arm movements is possible.

Time histories for pen, index finger knuckle, wrist (head of the radius) and forearm (midway between wrist and elbow) are digitised from video records. After smoothing (12 Hz, low-pass filter) pen displacement as a function of time may be plotted as shown in Figure A for one subject who employed a dynamic tripod penhold. The data shown is taken from the word "select" embedded in a sentence to be written either preferred size, one, or two steps larger where the steps were defined to give lower case heights in the region of 5 or 7.5 mms.

Figure B shows the vertical components of the pen velocity, of the hand about the wrist (velocity of the index knuckle with forearm motion partialled out) and forearm about the shoulder (velocity of the radial head) for two script sizes. It is interesting to observe that, while the forearm contribution appears almost negligible, there is a small in-phase contribution of the wrist to the vertical displacement of the pen. This would become more obvious if account were taken of relative lever lengths.


A
HORIZONTAL
ele
prefered
step1
step2
DISP. mm
TIME msec
VERTICAL
prefered
step1
step2
DISP. mm
TIME msec
B
VERTICAL
PREF. SIZE
pen
wrist
forearm
VELOCITY cms⁻¹
TIME msec
VERTICAL
SIZE STEP2
pen
wrist
forearm
VELOCITY cms⁻¹
TIME msec
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HORIZONTAL
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TIME msec
HORIZONTAL
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wrist
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VELOCITY cms⁻¹
TIME msec
D
HORIZONTAL
prefered
step1
step2
TIME msec
VERTICAL
prefered
step1
step2
VELOCITY cms⁻¹
TIME msec

Figure C displays the horizontal component of the velocities of the pen, hand about the wrist (index knuckle with forearm partialled out) and forearm (radial head). Again there is a clear in-phase relation between hand motion about the wrist and horizontal pen displacement at both script sizes.

Figure D presents the wrist components over the three script sizes. It can be seen that, allowing for phase shift between conditions, the contribution of wrist extension and flexion to both the vertical and horizontal displacement of the pen remains remarkably invariant over the three sizes of script. It may be concluded that this subject's penhold was sufficiently unconstrained to allow finger movements to effect changes in writing size. With a different penhold affording less freedom of finger movement, systematic changes in the relative contribution of finger hand and forearm movements would be expected and evidence for this would come from plots such as those shown.

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FURTHER EVIDENCE ON THE RELATIONSHIP BETWEEN FORM ERRORS IN PRESCHOOL PRINTING AND EARLY SCHOOL ACHIEVEMENT

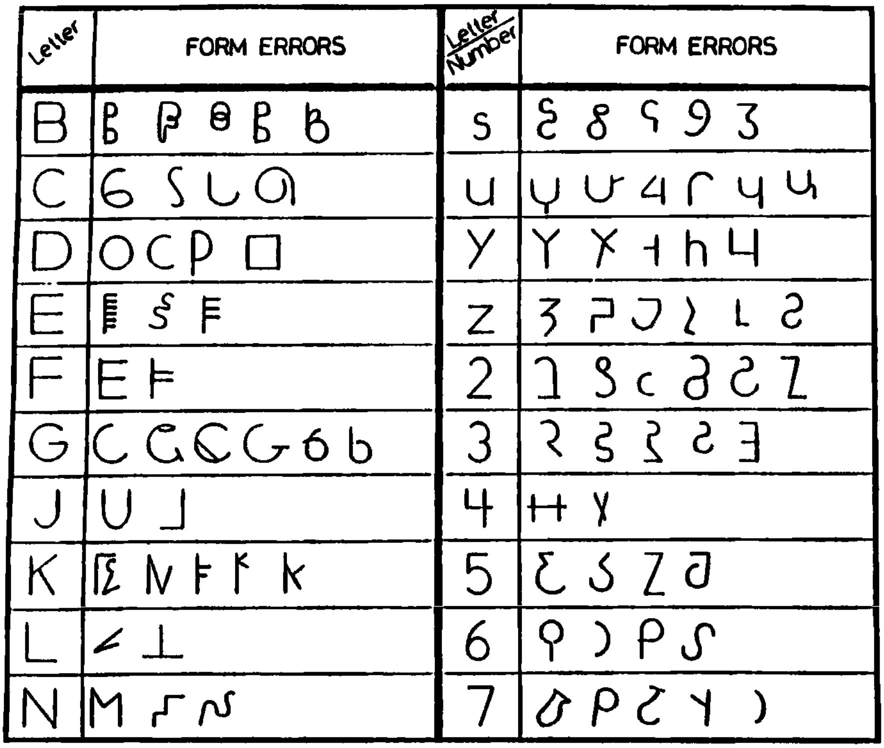
Marvin L. Simner

INTRODUCTION

When young children print it is not uncommon to find a backward '3' occasionally drawn in place of the letter S or the capital letter E containing four or more horizontal lines. Such errors are called "form errors" because they involve the addition, omission, and/or misalignment of parts leading to a marked distortion in the overall shape or form of the intended letter or number (for other examples see Figure 1). Although errors of this type have generated considerable interest for many years among investigators working with older children or adults, except for those who have been concerned primarily with the development of instructional techniques that could be used to help improve the legibility of the preschool child's printing (e.g., Furner, 1983; Staats, 1971) these errors have received little attention among people working with preschool children.

As an outgrowth of a series of investigations focusing on various aspects of young children's printing (Simner, 1979, 1981, 1982, 1984a, 1984b) we discovered, however, that form errors at the preschool level are far more important than previously thought and that they deserve serious study in their own right. Specifically, we found that when an excessive number of these errors appears in samples of printing obtained from four to six year old children, this can be an extremely important early warning sign of later school failure (Simner, 1982). Using procedures derived from this previous work we then developed the Printing Performance School Readiness Test (PPSRT) to provide a standardized means for identifying preschool children who exhibit this warning sign (Simner, 1985). The manual that accompanies the PPSRT contains the initial findings from a longitudinal investigation undertaken several years ago to evaluate this instrument. The major purpose of the present report is to update these earlier findings by presenting additional data from a further stage in this investigation.

Figure 1 Examples of form errors in children's printing (from Simner, 1982, reproduced with permission granted by the Editor-in-Chief of the *Journal of Learning Disabilities).*



SUBJECTS

As indicated in the manual, 619 non-repeating preschool children distributed among six different samples were obtained from public elementary schools situated in lower and middle income areas of London, Ontario, an urban center with a population of 275,000 people. Interviews conducted with a representative sample of 94 parents showed that the occupations of the parents of the children in this investigation ranged from laborer, construction worker, and custodian, through appliance technician, crane operator, and store manager, to school teacher, physician, and university professor. According to the Blishen (1967) scale for Canadian occupations the mean socio-economic index for this sample of parents was 38 on a scale that ranges from 25 to 76. In addition, although approximately 10-15% of the children who participated in this study came from bilingual backgrounds, all were fluent in English and, furthermore, all were in the appropriate grades for their ages (either pre-kindergarten or kindergarten) at the time the PPSRT was given.

Sample 1 contained 81 pre-kindergarten children (42 male, 39 female). Thirty-five of these children were tested in May/June 1980 while the rest were tested in May/June 1981. Sample 2 consisted of 69 pre-kindergarten children (38 male, 31 female) tested in May/June 1983 while Sample 3 was composed of 133 pre-kindergarten children (74 male, 59 female) tested in May/June 1984. The mean age for all of the children in Samples 1, 2, and 3 at the time of testing was four years, 10 months.

Sample 4, consisting of 118 kindergarten children (62 male, 56 female), was tested in October/November 1980. This sample also included 25 children from Sample 1. In addition, 110 of the children in Sample 4 were re-tested along with 10 new children at the end of the kindergarten year (May/June 1981). Sample 5, containing 132 kindergarten children (66 male, 66 female) was tested initially in October/November 1982. We also re-tested 105 of these children in May/June 1983 along with six other new kindergarten children.

Finally, Sample 6 was composed of 95 kindergarten children (40 male, 55 female) made up of two separate groups. The first group of 31 children was tested in October/November 1979 while the second group of 64 children was tested in May/June 1980. The decision to combine these two groups into one sample, despite the fact that they were tested at different times of the year, stemmed from the steady decline in group size that took place during the follow-up period. Prior to combining these two groups, though, we converted the form error scores obtained by the children in each group to z-score values to compensate for changes that normally take place in the number of form errors produced throughout the kindergarten year (Simner, 1982). The mean age of the children in Samples 4, 5, and 6 who were tested in October/November of kindergarten was five years, three months whereas the mean age for those tested in May/June of kindergarten was five years, 11 months.

METHOD

PPSRT Testing Procedure

Following the guidelines in the PPSRT manual each child, tested individually, was shown 41 letters and numbers presented one at a time on white cards held in a spiral binder. As mentioned above, testing took place either in the late spring of pre-kindergarten, the fall of kindergarten, or in the late spring of kindergarten. When testing occurred in kindergarten the children were required to print from memory immediately after seeing each letter or number for two to three seconds. This was accomplished by having the tester turn over the card that contained the letter and then ask the child to print the letter from memory. At the pre-kindergarten level the children merely copied the letters and numbers from the cards while the cards remained in full view. For both conditions total test time averaged about 10 minutes per child. After testing each protocol was scored for the presence of form errors using the detailed instructions that also are given in the manual.

Interscorer Reliability

Twenty randomly selected protocols were scored by fifteen university undergraduate students. In line with the evidence on interscorer reliability reported in the manual, the resulting product-moment correlations ranged from 0.87 to 0.98 (M=0.95) indicating the very high level of agreement that occurs when different people judge the overall number of form errors on protocols generated by this test.

Follow-Up Procedures

Each sample was followed for periods that ranged from one to three years. While every effort was made to locate all of the children as they progressed through school, budget restrictions prevented us from visiting schools more than once and from gathering information on children who moved to school districts outside of London. In addition, we did not obtain follow-up data on children who moved from the original public schools to denominational schools or to foreign language schools since the difference in curriculum that characterized these other schools, by itself, could have affected the children's performance on the various criteria discussed below. Although the children who were lost from our investigation for these reasons only represented approximately 20% of the total sample, it is important to note that the PPSRT scores obtained by these children were very similar to the scores obtained by the children who remained throughout the follow-up work. For example, both the mean PPSRT score (15.4) and standard deviation (8.1) for the 22 children in Sample 4 who were tested in the fall of kindergarten and then moved, were almost identical to the mean score (14.9) and standard deviation (8.7) produced by the 87 children in this sample who remained in the study through grade 2. Therefore, since both groups of children were quite similar at the outset, it would seem reasonable to conclude that this reduction in sample size probably had little impact on the correlations reported for the various measures discussed below.

Unfortunately, a similar conclusion is not justified in the case of those children who were eliminated from our follow-up work due to school failure. Specifically, once a child failed we could not collect meaningful achievement data beyond the grade in which failure took place since grade repetition, of course, entails exposure to material which clearly would have affected the children's performance on our criterion measures. Although only about 5 to 10% of the children in the various samples were lost for this reason, the mean PPSRT score for these children was far higher than the mean score for the group of children that remained in our investigation. (In the case of the Sample 4 children referred to above, the mean PPSRT score for the nine children who eventually failed either kindergarten or grade 1 was 27.4.) This difference in performance on the PPSRT is quite important in relation to the correlational findings reported below since the loss of these children served to reduce the range of individual differences in PPSRT scores among the children who remained throughout the follow-up work and it is well known that such a reduction in range tends to lower the magnitude of any resulting correlations (Anastasi, 1982). Also, the number of children in this failing group became progressively greater with each succeeding school year. For example, of the 12 children in Sample 1 who eventually failed, none repeated pre-kindergarten whereas two failed kindergarten and 10 were retained in grade 1. Hence, it should be kept in mind that the follow-up results reported in Table 1 probably underestimate the actual strength of the association between the children's initial scores on the PPSRT and the children's subsequent performance in school due to the progressive loss with each succeeding school year of these high scoring children.

School Achievement Criteria

Two independent sets of measures were employed as criteria of subsequent academic achievement. The first set consisted of the children's scores on the following standardized instruments administered either in pre-kindergarten, kindergarten, or 1st grade: the Wide Range Achievement Test (WRAT) by Jastak and Jastak (1976, Level-1); the alphabet knowledge, number knowledge, and relational concept subtests contained in Lesiak's (1978) Developmental Tasks for Kindergarten Readiness (DTKR); the word identification subtest from the Woodcock Reading Mastery Test (WRMT) by Woodcock (1974, Form-B); and the addition, subtraction, numerical reasoning, word problem, and time subtests from the Keymath Diagnostic Arithmetic Test (KDAT) by Connolly, Nachtman, and Pritchett (1971). In addition, two teachers provided us with the scores obtained by the children in their classes on the Metropolitan Readiness Test (MRT) by Hildreth, Griffiths, and McGauvran (1969) and on the Metropolitan Achievement Test (MAT) by Durost, Bixler, Wrightstone, Prescott, and Barlow (1971).

The second set of criteria was based on the children's classroom performance. At the end of both pre-kindergarten and kindergarten each child's class standing was obtained from the promotion lists prepared by the children's teachers using a 12 point rating scale with values that ranged from D– to A+. The information on these lists reflects the children's degree of mastery of the core curriculum objectives established by the Board of Education and, hence, the teachers' judgements of the children's overall readiness for promotion to the next grade. For those children followed through grades 1 and 2 we obtained the children's final report card marks issued in June, which also ranged from D– to A+, in the major subject areas of reading, written composition, and arithmetic. To determine the overall class standing for these children, we then calculated each child's average grade across these three subject areas.

RESULTS

Table 1 shows the product-moment correlations obtained between the children's performance on the PPSRT given either in pre-kindergarten (Samples 1, 2 and 3) or in kindergarten (Samples 4, 5 and 6) and the children's subsequent performance on these two sets of criteria (standardized test performance, classroom performance). As can be seen from the findings reported in Table 1, the correlations obtained between the total number of form errors produced in pre-kindergarten and in kindergarten and the children's later performance on the six different standardized tests mentioned above extended from 0.40 (Sample 2: Woodcock Reading Mastery Test, $df=38$, $p<.001$) through 0.79 (Sample 5: Wide Range Achievement Test, $df=130$, $p<.001$). Similar results were obtained in the case of the second set of criteria dealing with the children's subsequent classroom work where, with few exceptions, all the correlations ranged in the vicinity of 0.50 ($p<.001$). Moreover, as reported previously in the manual, based on the three independent samples of children that were given the same printing task twice, either four or eight months apart (see the Subjects section above), we obtained test-retest reliability correlations of 0.83 ($df=23$, $p<.001$), 0.73 ($df=108$, $p<.001$), and 0.74 ($df=103$, $p<.001$), respectively, between the total number of form errors produced during the first and the second test session. Considered together, the evidence from this follow-up work demonstrates that scores on the PPSRT at the preschool level are quite closely tied to later school achievement across the curriculum and, furthermore, that preschool children who perform either very poorly or very well on this test on one occasion are likely to behave in an extremely similar fashion when tested again even up to half a year later.

Through a further analysis of the data we also found that the PPSRT can be employed with reasonable accuracy in identifying individual children who are likely to experience later school failure. First, using the general guidelines suggested by Lichtenstein (1981) as well as Keogh & Daley (1983), the children were divided into two categories based on the teacher's end-of-year promotion decisions. Those children said to be 'at-risk for failure' either were not promoted or, if promoted, they were placed in a slower or junior section of the next grade. For the most part these were the children who received D–, D, or D+ ratings on the 12 point scale mentioned above. The other category, labeled 'fully-ready for promotion,' refers to children who obtained an overall rating of B– to A+ on this same scale. This label was used because these ratings were awarded only to children who were not experiencing major problems in any of the main academic areas covered in the primary grades. It is important to note, however, that because of attrition,

Table 1 Product-moment correlations between subsequent performance in school and scores on the printing performance school readiness test administered in pre-kindergarten (samples 1, 2, and 3) or in kindergarten (samples 4, 5, and 6).

		STANDARDIZED TEST PERFORMANCE								ACADEMIC PERFORMANCE IN SCHOOL											
		PRE-K		KINDERGARTEN			1st GRADE			END-OF-YEAR OVERALL IN-CLASS PERFORMANCE				END-OF-YEAR REPORT CARD MARKS					
														1st GRADE			2nd GRADE		
		DTKR	WRAT	DTKR	MRT	WRAT	MAT	WRMT	KDAT	PRE-KINDERGARTEN	KINDERGARTEN	1st GRADE	2nd GRADE	READING	WRITTEN COMPREHENSION	ARITHMETIC	READING	WRITTEN COMPREHENSION	ARITHMETIC
SAMPLE 1	SPRING OF PRE-K (N=81)									*** .50 (N=80)	*** .60 (N=70)	*** .51 (N=65)	** .38 (N=52)	*** .47 (N=65)	*** .46 (N=64)	*** .45 (N=65)	** 38 (N=52)	* .27 (N=51)	** .37 (N=52)
SAMPLE 2	SPRING OF PRE-K (N=69)		*** .76 (N=62)			*** .67 (N=60)		*** .40 (N=40)	*** 60 (N=40)	*** .43 (N=69)	*** .48 (N=60)	*** .54 (N=51)		*** .56 (N=51)	*** .55 (N=50)	*** 43 (N=51)			
SAMPLE 3	SPRING OF PRE-K (N=133)	*** .50 (N=115)								*** .59 (N=133)	*** .51 (N=104)								
SAMPLE 4	FALL OF KINDER. (N=118)				*** .58 (N=22)		*** .74 (N=20)	*** .50 (N=88)	*** .57 (N=84)		*** 54 (N=118)	*** 60 (N=98)	*** 51 (N=87)	*** .53 (N=98)	*** .48 (N=89)	*** .54 (N=98)	*** .50 (N=87)	*** 42 (N=85)	*** 39 (N=87)
	SPRING OF KINDER. (N=120)				*** .59 (N=21)		*** .76 (N=22)	*** .50 (N=92)	*** .61 (N=88)		*** 58 (N=120)	*** .53 (N=103)	*** .54 (N=85)	*** 48 (N=103)	*** 53 (N=93)	*** 52 (N=103)	*** .53 (N=85)	*** .49 (N=83)	*** 42 (N=85)
SAMPLE 5	FALL OF KINDER (N=132)			*** 68 (N=132)		*** .79 (N=132)		*** .59 (N=82)	*** 75 (N=82)		*** .63 (N=127)	*** .53 (N=100)	*** 57 (N=75)	*** 54 (N=100)	*** 49 (N=89)	*** .44 (N=100)	*** 54 (N=75)	*** 58 (N=75)	*** 47 (N=75)
	SPRING OF KINDER (N=111)			*** 44 (N=106)		*** .72 (N=102)		*** 53 (N=80)	*** .71 (N=80)		*** 47 (N=111)	*** 49 (N=93)	*** 45 (N=66)	*** .51 (N=93)	*** 49 (N=82)	*** 43 (N=93)	*** .37 (N=66)	*** .45 (N=66)	*** 42 (N=66)
SAMPLE 6	FALL OR SPRING OF KINDER (N=95)										*** .59 (N=89)	*** .54 (N=76)	*** .46 (N=57)	*** 50 (N=76)	*** .51 (N=69)	*** .48 (N=76)	*** .51 (N=57)	*** .41 (N=56)	*** .41 (N=56)

* p<.05
** p<.01
*** p<.001

only the most recently available information could be used in determining which of the two categories best described a given child. That is to say, grade 2 information was employed for those children whom we were able to follow through this level. In the case of other children, even in the same sample, it was sometimes necessary to employ either grade 1, kindergarten, or even pre-kindergarten information depending on when the children were lost from the sample. In other words, had it been possible to follow all of the children to the same grade level, the results reported below might have been somewhat different.

Next, cutoff points for school readiness on the PPSRT were determined following Simner's (1982) procedure. For children tested in the spring of pre-kindergarten the cutoff point was set at a form error score of 22, for children tested in the fall of kindergarten the score was set at 17, and for children who were tested in the spring of kindergarten the score employed was 6. Tables 2, 3, and 4 show the number and percentage (in brackets) of children in the at-risk as well as in the fully-ready category for whom either true or false positive as well as true or false negative judgements occurred using these cutoff points. As the findings in these three tables indicate, with these cutoff points we were able to identify correctly a large majority of the at-risk children (true positives) in Samples 1 through 6 while at the same time achieving a mean classification hit rate of 79%.

Table 2 Prediction of teacher's end-of-year performance evaluations from PPSRT scores obtained in the *late spring of pre-kindergarten* (samples 1, 2 and 3 combined).

	at-risk for failure	fully-ready for promotion
Poor Prognosis (score of 22 or more)	(true positives) 39 (67%)	(false positives) 20 (14%)
Good Prognosis (score less than 22)	(false negatives) 19 (33%)	(true negatives) 120 (86%)

Classification hit rate: True positives + true negatives/total sample = 80%

Table 3 Prediction of teacher's end-of-year performance evaluations from PPSRT scores obtained in the *fall of kindergarten* (samples 4, 5 and 6 combined).

	at-risk for failure	fully-ready for promotion
Poor Prognosis (score of 17 or more)	(true positives) 57 (86%)	(false positives) 33 (26%)
Good Prognosis (score less than 17)	(false negatives) 9 (14%)	(true negatives) 96 (74%)

Classification hit rate: True positives + true negatives/total sample = 78%

Table 4 Prediction of teacher's end-of-year performance evaluations from PPSRT scores obtained in the *late spring of kindergarten* (samples 4, 5 and 6 combined).

	at-risk for failure	fully-ready for promotion
Poor Prognosis (score of 6 or more)	(true positives)	(false positives)
	62 (90%)	38 (28%)
Good Prognosis (score less than 6)	(false negatives)	(true negatives)
	7 (10%)	99 (72%)

Classification hit rate: True positives + true negatives/total sample = 78%

Finally, the information in Table 5 supplements the results in Tables 2, 3, and 4 by showing the approximate odds of being at-risk for school failure as opposed to being fully-ready for promotion for various ranges of scores both above and below these cutoff points. To arrive at these odds we used a procedure described in Stanley (1965, pp. 101-102). This involved first determining the number of children in the at-risk as well as in the fully-ready category whose form error scores fell within the ranges shown in Table 5. Next, the odds of being at-risk as opposed to being fully-ready were obtained by calculating the ratio of these two numbers. The evidence in Table 5 clearly indicates that, as the total number of form errors obtained by any given child approaches the maximum of 41, the probability of that child being at-risk, instead of being fully-ready for promotion, increases substantially.

DISCUSSION

In sum, the results from this longitudinal investigation show that the PPSRT can be scored reliably, that it generates performance at the preschool level which remains quite stable over a fairly long period of time, and that this preschool performance is closely tied to later achievement in each of the major areas of the elementary school curriculum. Therefore, to the extent that correct early identification of the at-risk preschool child is important for the prevention of early school failure, as many have argued (e.g., Reynolds & Clark, 1983), it would certainly seem that form errors in printing at the preschool level, as measured by this test, can offer a useful source of additional information to educators and psychologists when they must decide which preschool children require special academic assistance. Before employing the PPSRT for this purpose though, it would seem important to ask why form errors occur and then to consider the nature of the assistance that

Table 5 Approximate odds of being at-risk for school failure as opposed to being fully ready for promotion for various score ranges on the PPSRT. The number of at-risk and fully-ready children who obtained scores in these ranges is also shown below.

	PPSRT Score Range	Number of Children At-Risk	Fully-Ready	Approximate Odds Of Being At-Risk
Late Spring of	31 to 41	19	2	10:1
Pre-kindergarten	22 to 30	22	18	1:1
(Samples 1, 2,	13 to 21	8	22	1:3
and 3 combined)	0 to 12	9	98	1:10
Fall of Kindergarten	30 to 41	23	3	7:1
(Samples 4, 5, and	17 to 29	34	30	1:1
6 combined)	10 to 16	6	29	1:5
	0 to 9	3	67	1:22
Late Spring of	17 to 41	24	1	24:1
Kindergarten	6 to 16	38	37	1:1
(Samples 4, 5, and	3 to 5	6	56	1:10
6 combined)	0 to 2	1	43	1:43

should be given to children who produce an excessive number of these errors if these children are to avoid school failure.

One possible explanation is that form errors could stem from perceptual problems, motor problems, or perceptual/motor integration problems. The reason we offer this explanation is the striking similarity between these errors and other drawing as well as writing errors that, in the past, typically have been attributed to perceptual/motor difficulties (see, for example, Berry & Buktenica, 1967; Hallahan, Kauffman, & Lloyd, 1985; Koppitz, 1963). If this explanation is correct, it would then seem reasonable to recommend placing children who produce a large number of form errors in intervention programs like the ones developed by Barsch, Getman, Frostig, Kephart and others which emphasize early perceptual/motor training. This recommendation, of course, is based on the fact that such programs often are suggested as being the most appropriate way to reduce the likelihood of later school failure for children who suffer from perceptual/motor problems (Hammill & Bartel, 1975).

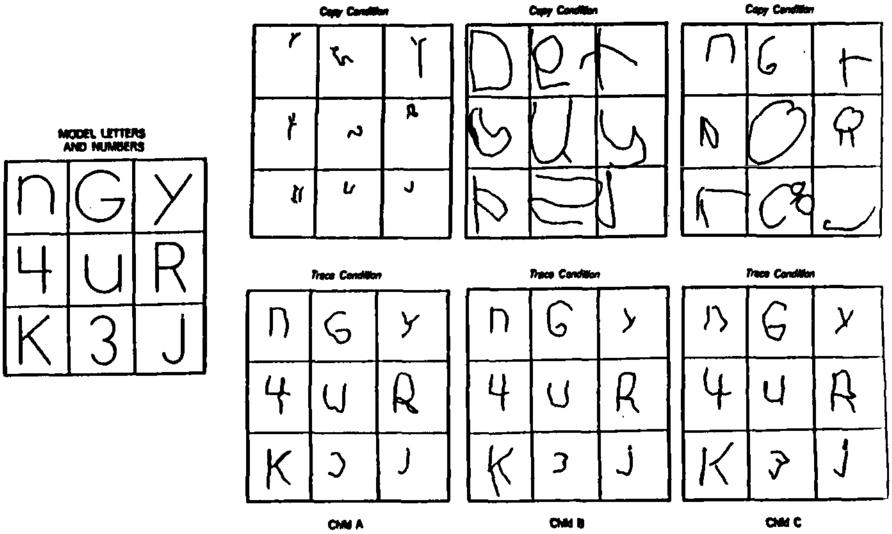
Prior to accepting this explanation or making this recommendation, however, there are three additional findings that should be taken into account. First, we reported elsewhere (Simner, 1979) that form errors are far more common when kindergarten children print from memory immediately after seeing pictures of letters and numbers than when they print while looking directly at these pictures. Second, in this same study we also found that merely focusing the kindergarten child's attention on the printing task itself, without providing the child with any practice in letter or number formation, produces a marked reduction in the number of form errors. Third, in a more recent study we asked 22 pre-kindergarten children, whose scores on the PPSRT exceeded the at-risk cutoff point shown in Table 2, to copy as well as to trace nine model letters and numbers selected from among the 41 letters and numbers used in the PPSRT. Under the copy condition the procedure that we employed was identical to the one described in the Method section above. Under the trace condition each letter/number (presented one at a time as in the copy condition) appeared beneath a plain white sheet of paper. Here the child was asked to print directly over the letter as seen through the paper. Both conditions were administered to each child in the spring semester of pre-kindergarten using a counterbalanced order.

The outcome of this more recent work demonstrated quite clearly that whether or not form errors occur, even among children who do produce an excessive number of these errors, depends to a considerable extent on the nature of the printing task itself. Specifically, the number of form errors generated when these 22 children traced ($M=2.3$) was significantly lower than the number generated when these children copied ($M=6.4$; $t(21)=7.41$, $p<.001$). Figure 2 provides a graphic illustration of this finding by showing the nine model letters and numbers the children were asked to reproduce under these two different test conditions along with sets of protocols obtained from three of the 22 children who took part in this study. By comparing the reproductions generated under both the trace and the copy condition against the model letters and numbers shown in Figure 2, it can easily be seen that when the children traced, the overall quality of their printing was indeed substantially better.

In light of this further evidence we believe there is good reason to question whether in fact form errors do stem from perceptual/motor difficulties. That is, do form errors result because children are unable to see letters as they actually appear (which would indicate a perceptual problem)? Do they occur because children cannot execute the fine muscle movements required to reproduce letters (which would indicate a motor problem)? Or do they stem from children's inability to combine the visual information they receive from the letters with the motor output needed to make a correct reproduction of the letters (which would indicate a visual/motor integration problem)? Presumably, if any one or even some combination of these three factors were valid, we should not have obtained the findings summarized above since it is not clear how the various manipulations employed in the foregoing studies could have corrected problems of this nature. In short, because the outcome of this work casts some doubt on the assumption that form errors result from perceptual/motor difficulties, we feel that it might not be beneficial to place children who make these errors in perceptual/motor training programs.

If form errors do not result from perceptual/motor problems, what then could be responsible for their occurrence and how should we help children who frequently make these errors? As an alternative to this perceptual/motor

Figure 2 The nine model letters and numbers used in the copy/trace study and the reproductions of these same letters and numbers made by three pre-kindergarten children tested under both the copying and tracing conditions in this study.



account we suggested previously that form errors in printing might be due to the combined effects of momentary lapses in the child's attention to detail and to the child's lack of familiarity with letters and numbers (Simner, 1982, 1985). Since there is a considerable body of evidence linking these two characteristics by themselves to later poor performance in school (Simner, 1982, 1983), we then proposed that to avoid school failure, the at-risk preschool child who produces an excessive number of form errors might profit from being in a highly structured compensatory education program. In other words, a program that would focus and maintain the child's attention while providing the child with increased drill in language-based materials. Indeed, there is also evidence which shows that programs like this can be quite effective in reducing the odds of school failure among children who appear to be very similar to the children in our investigation who produced many form errors (see, for example, Becker & Gersten, 1982; Rhine, 1981). Therefore, rather than assign children whose scores exceed the cutoff point on the PPSRT to perceptual/motor training programs, it would seem reasonable to us to recommend instead, that these children should be placed in programs similar to the one described in Becker and Gersten, since programs of this type are likely to be much more suitable in meeting the particular needs of the at-risk children who are identified through use of this new printing test.

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EFFECTS OF FEEDBACK TRAINING ON 'NORMAL' AND DYSGRAPHIC STUDENTS

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INTRODUCTION

An important situational condition which influences the quality of writing, is the availability of sensory feedback (Adams, 1971). Presuming the individual can perceive the information developed by his own performance and regulate his further actions correspondingly, the feedback mechanisms are supposed to facilitate the learning and performance of any psychomotor task. The effects of feedback, however, depend on the nature of the task and the kind of feedback being used. Previous studies have indicated that children can be trained efficiently with regard to sensorimotor feedback control in tracing, tracking, and copying task (Søvik, 1980, 1981), and significant relationships have been disclosed between tracking, copying, and handwriting (Søvik, 1974, 1979, 1981; Townsend, 1951). As the tracking task in a writing-related training program seems to offer the child an opportunity to exploit the system of sensory feedback, such activities have been used both in research and educational programs.

Instruction can also function as feedback. The term supplementary feedback is now being used to explain the interactions taking place between the instructor's verbal and/or motor demonstrations of the learning tasks and the information which the individual receives by sensory/knowledge feedback while doing the task (Singer, 1982; Søvik & Teulings, 1983). Further, previous studies have shown that persistent, dynamic tracking can provide the learner with sensory as well as supplementary feedback when doing copying tasks (Søvik, 1979, 1981). When a child is doing a dynamic tracking task in cooperation with another person (e.g., an instructor) the concept of social tracking has been used. It includes sensory and supplementary feedback. It means real-time measurement of behavioral interactions between individuals and cover the meaning of interactional processes taking place between student and instructor in the same situation.

In our previous studies of testing the effects of various training programs with sensory/supplementary feedback of children's writing performances, two methods emphasizing either the principle of social tracking or computer-assistant instruction (CAI) have been applied. The CAI-system improved children's writing performances with concern to speed, but no significant data were achieved with respect to writing accuracy and smoothness (Søvik & Teulings, 1983). On the contrary, the study in which the training program was performed with dynamic, social tracking only, the findings were in favor of children's accuracy-scores without trading off the writing speed (Søvik, 1981). In fact, social tracking seems to be preferable to children suffering from writing difficulties (Søvik, 1984). Even though a computer and/or video system can be very useful in training children writing in accord with the feedback theory, the principle of dynamic, social tracking seems to be more recommendable to examine the impact of feedback on various writing variables.

As the speed and accuracy parameters in children's functional writing can be improved by training programs based on the feedback theory, it is reasonable to believe that the characteristics of the writing behavior can be changed as well. Results from earlier research carried out to investigate whether there is an invariance in the time domain or not, even when the overall speed of a continuous writing movement is intentionally changed, has given no reliable clues so far (Søvik & Teulings, 1983; Viviani & Terzuolo, 1980). However, each writing pattern (task) requires its own general characteristics which is supposed to differ across subjects owing to the individual way of writing. Also, changes in the shape of the individual velocity curves of such a task can be observed over time (Søvik & Teulings, 1983). Consequently, one may theorize that training programs organized to develop a more efficient way of coordinating the writing movements (smooth writing), can change space-time relations in children's handwriting.

Unfortunately, former studies have not taken the three parameters accuracy, smoothness, and speed into account simultaneously. In other words, it remains to be investigated whether an experimental program of individualized instruction based on dynamic social tracking mainly, will cause a progress in children's copying and writing performances with regard to accuracy, smoothness, and speed (Problem 1).

Whereas the majority of earlier studies, focused on the effects of feedback on writing behavior, have used adults or 'normal' children as subjects, few investigations in the field have paid attention to children suffering from writing problems. Such children can also be found in ordinary school-classes, and they are categorized as dysgraphic children when their writing problems can be characterized as serious and as specific learning disabilities. Dysgraphy can shortly be defined as problems in executing manual writing without having any overt, perceptuo-motor handicap. The term itself does not explain a poor handwriting performance in general. It refers to children whose academic achievements are discrepant with his poor writing behavior (Søvik, 1984). Dysgraphy, then, does not necessarily have to be caused by developmental, organic defects termed as clumsiness, even though the majority of the dysgraphic children will be clumsy (Brenner, et al., 1967; Gubbay, 1975). Although mental retardation and poor handwriting performance are found to be closely related (Søvik, 1975), this category (retarded) will be excluded from the present study.

Since the dysgraphic children constitute an important group of subjects with learning disabilities they were viewed to be a group of useful comparison to the 'normal' children of equal age when studying the problems raised in the present research project. Some related prestudies had shown that the effects of training in social tracking were significant to both categories of children (Søvik, 1981, 1984; Søvik & Teulings, 1983). Hence, the theoretical and empirial background gave reasons for expecting that the experimental program mentioned in conjunction with Problem 1 would have an impact on the dysgraphic subjects as on the 'normal' ones under study (Problem 2).

METHOD

Design and Sampling

The design and sampling procedure of the present study can be grouped into phase 1 and phase 2. During phase 1 a survey research was done in 10 school-classes (Grade 3), randomly selected in Trondheim Public Schools, to screen subjects (Ss) for the experiment (phase 2). A test battery consisting of a visual-motor-integration test and diagnostic tests in reading, spelling, and handwriting were administered to pupils in the 10 classes. In addition, the same pupils were rated by their teachers with regard to skills in: language, reading, spelling, and motor behavior. A test of mental ability (WISC-R) and a visual perception test (SCFGT) were administered to Ss defined as dysgraphic children.

When students in the 10 classes had been stratified on their writing ability ('normal' and dysgraphic children), 10 'normal' and 10 dysgraphic children were randomly selected as Ss for the experiment. Finally, each of these two groups of Ss were randomly selected for the experimental group (E-group) and the control group (C-group). By using five Ss in each of the cells in this 2x2 pretest-posttest control-group design, adequate power for analysis and statistics seemed to be guaranteed (Hays & Winkler, 1971). All Ss received ordinary writing exercises at school which did not interfere with our experiment. Both C- and E-group were tested before and after the treatment sessions.

Instrumentation

Both experimental program, pre- and post-tests were performed in a "Cybernetic Laboratory" (Søvik, 1979). It consists of a double, closed circuit TV (CCTV) that enables the experimenter (E) to project his pen-position from below onto the S's writing paper. Simultaneously, it allows E to monitor on a display whatever the Ss see and what they write. This CCTV was used during the treatment sessions which were run only with the E-group.

In some of the pre- and post-tests, however, a combined system of this CCTV and a computer-system was used. Before the pre-tests started, the test-items (tracking and copying tasks) had been written on and recorded by means of a computer-controlled Summa-graphics BIT-PAD-one digitizer with a normal-looking electronic pen with ball-point cartridge which was connected to the digitizer via a flexible wire. Points were registered whenever a change in the position of the pen was 1 mm. in the X- or Y-direction. Sampling rate will therefore vary from 0 to 125 coordinate pairs/sec. on the digitizer. The coordinates of the pen tip were determined and transmitted to a SAGE IV digital micro-computer, with M 68000 processor and dual floppy in which the signals were processed and stored on diskette for later use. Data were adapted for display monitor that test-items (written by E) could be reviewed to S for performance (copying or tracking).

Three different procedures were applied in executing the experimental program of dynamic, social tracking in laboratory. Usually, each treatment session would begin with individual instruction repeating/practising correct grip of chalk/pen, and by showing S how writing movements could be coordinated in a reasonable way. The exercises were demonstrated and explained on board by E before S practised the tasks. The same exercises and some additional tasks were then used for treatment by means of CCTV. In this situation, the principles of tracing and/or tracking were following to train Ss for 'correct' writing motion (coordination of movements, moving the hand/arm properly, etc.), adequate speed, and precise size and forms (in accord with model/speed shown by E). Every time Ss came to the laboratory some 60 min. (with a short break) were used for general and individual exercises.

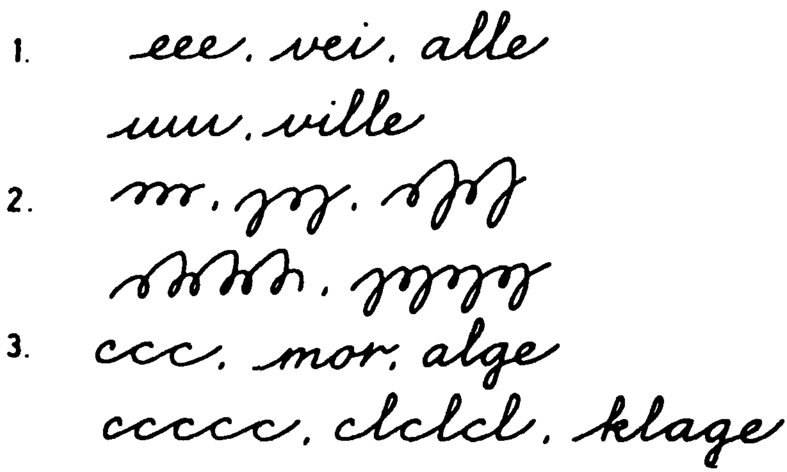
The system described above was also used while collecting data for testing the smoothness in S's writing (the word 'arkade'). Data consisted of X- and Y-coordinates and the related time. After the experiment the processed data could be used for various analyses. One of the analyses was done to produce the absolute velocity curve as a function of time. These curves could be displayed in a QUME 211 GX graphic terminal placed near E. The curves could also be plotted on paper by an EPSON HI-80 plotter.

A special set-up was arranged in the laboratory to perform the pre- and post-tests of the accuracy of handwriting (writing a sentence). S's writing behavior was then video-taped by means of a video-camera, type SONY AVC 1450 CE (low light), and a video-recorder, type SONY SL-C7.

Experimental Program and Performance

An experimental program of individualized instruction in graphic exercises was developed and used by E and Ss during treatment sessions (3 weeks) in laboratory Ss' performances on tests done at school (phase 1) and pre-tests in laboratory were used diagnostically for the purpose of having the experimental program developed and adapted to Ss. It consisted of general treatments given to all 10 Ss in the E-group, and individual exercises/procedures. Both kinds of treatment were organized as 'free' exercises done on a blackboard or a paper apart from the CCTV and graphic exercises performed by means of the CCTV. The graphic exercises which dominated the treatments were both meaningless tasks (guirlands, archades, or combinations of both) and separate letters or words. In Figure 1 some examples are given of the writing exercises that were used in the experimental program.

Figure 1 Some examples of writing patterns. Group 1 consists of guirlands, group 2 of arcades, and group 3 of combinations of both.



No time limit was set in experiments, but verbal comments were given by E to S about S's tracing or tracking behavior when it was found to be somewhat incorrect.

There were two treatment sessions per week, i.e., six sessions in all. The training in the laboratory was performed individually. Ss in control group had no training in the laboratory, but they received ordinary training in handwriting (two times per week at school).

Dependent Variables, Data Collection, and Scoring of Data

The dependent measures used as pre- and post-tests were as follows:

1. Test of accuracy in functional writing in which the timescore (measure of general writing speed) was included. The test was performed in two ways: Firstly, S wrote the sentence: "Den flinke grå katten gjorde høye hopp over den biske hunden" while his writing was video-taped and timed. Secondly, S wrote the word 'arkade' on the digitizer, and data were stored on the computer. In both cases there were two sets of data, one set which consisted of S's writing products left on paper, and another set which was information on S's writing behavior.
2. Test of accuracy in copying. In this test S was supposed to copy the test-items on paper as well as he could. Two persons, training in advance, rated the graphic products purchased by the tests of accuracy in functional writing and copying. When scoring the specimen the raters used a scale of 1 to 7 points. As to inter-rater reliability, cf. earlier studies (Søvik, 1981, 1984).
3. Test of smoothness (coordination of finger/hand movements) in writing. It has already been mentioned that S's writing rhythm was registered and stored in the computer when he wrote the word 'arkade' on the tablet (digitizer). Analyses of the characteristics of S's individual, absolute velocity curves of the two parts 'ark' and 'ade' of the word 'arkade' were done in accord with the following criteria: 1. To observe changes in overall writing speed from pre- to post-test. 2. To note maximum absolute velocity (mm/sec.) in pre- and post-tests. 3. To analyse the individual velocity curves in pre- and post-test in view of a) general writing pattern (rhythm), b) the amplitudes within the various parts of the curve and, c) numbers and lengths of interruptions during the execution of the task.

After the absolute velocity curves of the pre- and post-test performances had been compared, the individual curves were also analyzed and compared with a model curve. The model was developed on account of the writing of 'arkade', done by an adult whose coordinations of writing movements (rhythm) were on a high level (very smooth writing). Since the curves functioned as a reference ("ideal"), it was called a model.

RESULTS

Table 1 presents product-moment (PM) correlations among variables used as pre- and post-tests in the present study. It can be noted that correlations between variables which belong to one another as pre- and post-tests in general are positive and significant findings. Moreover, correlations between variables measuring accuracy of performance in copying and writing (separate word and sentence) are high positive coefficients. Similarly, the interrelationships among variables measuring writing speed are high and significant, whereas the correlations between accuracy-scores and speed-scores are negative or close to zero. As to error-scores in tracking-ability they disclose negative relations to the accuracy-scores and positive relations to the speed-scores. The findings are reasonable as higher scores on tracking mean more errors which usually correspond with fast skill performance.

Table 1 Product-moment correlations among variables used as dependent measures. N = 20.

Variable*	1	2	3	4	5	6	7	8	9	10
2	.50									
3	.87	.32								
4	.45	.74	.32							
5	.79	.27	.64	.37						
6	-.37	-.29	-.25	-.38	-.18					
7	-.36	-.33	-.31	-.54	-.38	.65				
8	-.14	.20	-.25	-.17	-.14	.21	.09			
9	-.41	.14	-.55	-.30	-.36	.34	.55	.52		
10	-.34	-.47	-.31	-.63	-.17	.53	.53	.70	.12	
11	-.42	-.49	-.45	-.74	-.37	.42	.64	.43	.51	.74

*Variable 1: Post-test in copying (accuracy-score) (12 items)
" 2: Pre-test in writing (" ") (word 'arkade')
" 3: Post-test in " (" ") (" ")
" 4: Pre-test in " (" ") (sentence)
" 5: Post-test in " (" ") (")
" 6: Pre-test in " (speed-score) (work 'arkade')
" 7: Post-test in " (" ") (" ")
" 8: Pre-test in " (" ") (sentence)
" 9: Post-test in " (" ") (")
" 10: Pre-test in tracking (error-score) (12 items)
" 11: Post-test in " (" ") (" ")

Analyses of Covariance

Analyses of covariance were carried out on each of the six criterion variables. In each of the analyses, the related pre-test was used as a covariate.

Even though the effects of the experimental program were in focus of the present study (Experimental group vs. Control group), the effects of second factor ('Normal' vs. Dysgraphic group), and the interaction effects were always measured in each of the analyses.

As to data from analyses of covariance using copying as dependent measure, it gave a significant finding in favor of the E-group ($F(1,19)=4.04$, $p=.06$). Although the N-group performed better on the copying test as did the D-group, the finding was not significant. No significant interactions were found. According to Table 2, Ss in the E-group have improved the accuracy-scores of their writing performances from pre-to post-test considerably. Ss in the D-group had the greatest progress.

A significant difference between the E-group and the C-group was also disclosed in favor of the experimental program concerning accuracy in writing a sentence (F(1,19)=11.22, p=.01). A slight difference in favor of the N-group was notified, but the difference was not significant. Comparisons between figures in Table 2 will indicate that the D-group has profited more from the treatment-program than the N-group, thus having reduced the difference between the groups which existed when entering the experiment.

Further, the analysis of covariance with accuracy-score in writing the word 'arkade' gave no significant findings. However, it can easily be noted that the E-group made some progress during the period of experimentation, and again Ss in the D-group seem to have improved their writing performances more than Ss in the comparable group. No significant interactions were found. Analysis of covariance using speed-scores in writing a sentence as criterion gave no significant differences between the groups under examination, or interaction effects.

Table 2 Average pre- and post-test scores on dependent measures for the four categories of Ss. N=20.

Test:		E-group	C-group	N-group	D-group
COPYING	pre-test	43.00	43.22	48.56	38.20
	post-test	52.00	45.60	50.20	47.40
WRITING (sentence)	pre-test	3.60	3.78	4.94	2.55
	post-test	4.30	3.39	4.11	3.65
WRITING (word)	pre-test	3.13	3.71	4.08	2.94
	post-test	3.88	3.29	3.83	3.44
WRITING-SPEED (sentence)	pre-test	106.10	128.70	104.80	130.00
	post-test	92.70	113.20	87.70	118.20
WRITING-SPEED (word)	pre-test	17.90	14.90	15.26	17.54
	post-test	22.11	17.55	15.86	23.80

However, the slight difference found between the E- and C-group on post-test indicated that the C-group wrote more slowly than the E-group. Similarly, the D-group wrote more slowly than the N-group on the same test. Also, data in Table 2 confirm a progress in speed-scores from pre- to post-test for all groups, and Ss in the N-group always are writing somewhat faster than the dysgraphic Ss. It is reasonable to compare the findings of the final analysis of covariance with speed-scores in writing the single word 'arkade' as dependent measure with data referred to above. Concerning the difference between the N- and the D-group the trend is the same. The D-group writes more slowly than the N-group, and the difference is significant ($F(1,19)=3.81$, $p=.07$). The tiny difference detected between the E- and C-group, however, was in favor of the C-group. It should also be noted that all four groups wrote the word 'arkade' faster in the pre- than in the post-test. No dependable interaction effects were revealed in any of the tests recording the total (average) writing speed.

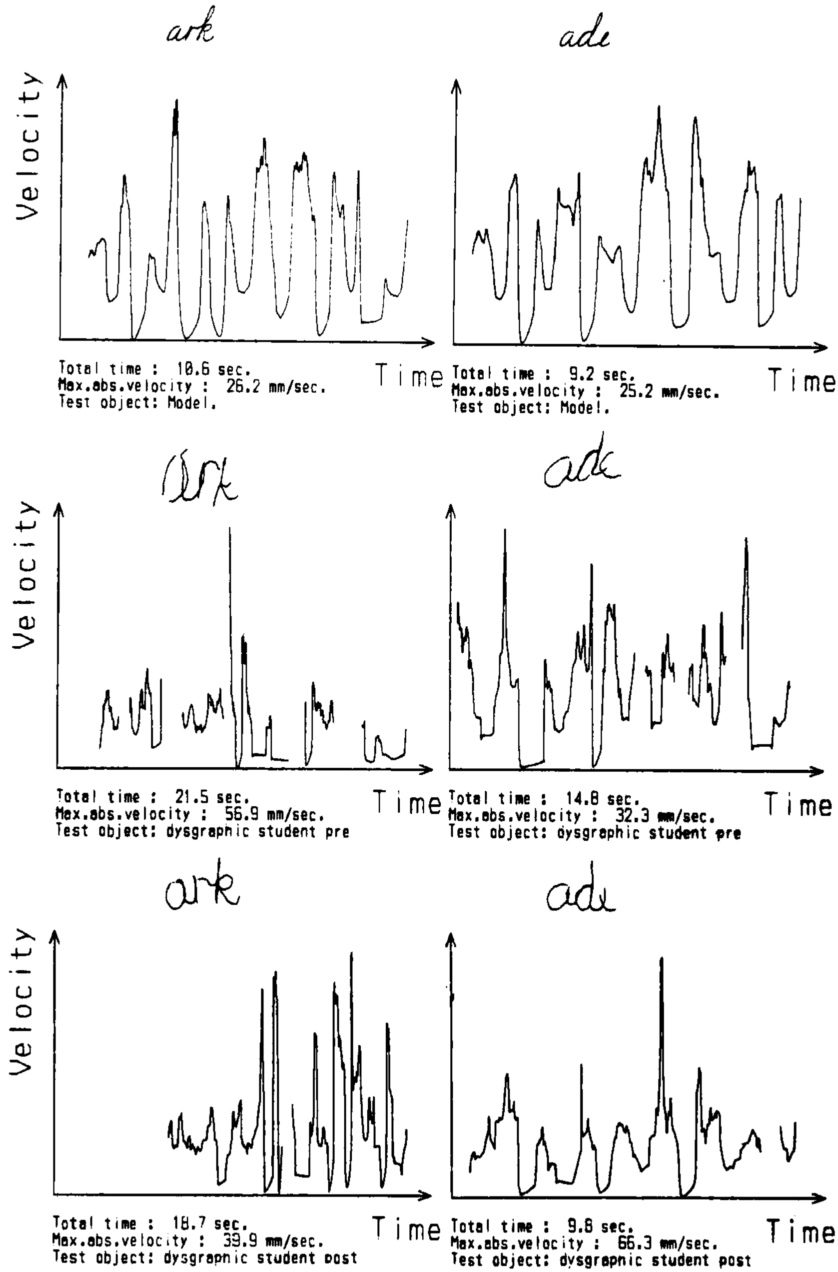
Analyses of the Absolute Velocity Curves

Owing to space considerations only the model-curve(s) and the individual curves of the pre- and post-test performances of a dysgraphic S are presented in Figure 2. It can be noted that this S wrote considerably faster in his post-test (56.9+32.3=89.2 sec. vs. 18.7+9.8=28.5 sec.), whereas his maximum absolute velocity (m.a.v.) had increased from pre-to post-test (56.9 mm/sec. vs. 66.3 mm/sec.), but this was found in the 'ade'-part only. In general, his writing pattern has changed during the treatment period towards a more 'natural' rhythm, i.e., a pattern of rhythm usually found with good writers (regular movement patterns), even though it was not equal to the pattern of the model. As far as the amplitudes of the two paris of S's curves are concerned they have not changed much from pre- to post-test, but there are fewer interruptions (horizontal lines and breaks/-openings in the curve) in the post-test. All in all, there are reasons to conclude that the treatments have caused an alteration in S's writing behavior, i.e., he seems to have achieved a more smooth writing pattern at the end of the experiment.

In analyzing and assessing the absolute velocity curves of Ss in the E-group, the following trends were disclosed: The majority changed the average speed of their writing during the treatment period. Those writing very fast in pre-test (6 Ss) would spend more time on their writing during the post-test, whereas the remaining Ss then wrote with increased speed-scores. Further, reduced m.a.v. was found from pre- to post-test for eight Ss. On the other hand, the general writing pattern and average sizes of the amplitudes of the curves of Ss' writing performances did not change much from pre- to post-test. Seven Ss, however, had fewer interruptions in their post-test writing. To sum up: Most of the 10 Ss in the E-group had produced absolute velocity curves in the post-test which were more in line with the writing pattern of the model than they did in the pre-test. The five dysgraphic Ss seemed to have had a relatively greater progress in developing a more smooth writing pattern than the 'normal' Ss.

When analyzing the curves of Ss in the C-group the following trends were found: Four Ss, most of them from the D-group, had decreased average writing-speed in their post-test compared to their pre-test, and only two Ss had achieved significant lower m.a.v. from pre- to post-test. As to the general writing motion and amplitudes of the curves of Ss in the C-group, no considerable changes were found during the period of experimentation. Only two of the 'normal' Ss had curves which resembled the one of the model. Neither could an alteration in average number of interruption in the curves

Figure 2 Model-curve(s) and individual curves of the pre- and post-test performances of a dysgraphic S.



of the C-group be observed from pre- to post-test. To sum up: In comparison with the model, Ss in the C-group did not in general improve the smoothness of their writing behavior during the experiment, and no significant changes of their writing motion were found from pre- to post-test performance.

CONCLUSIONS AND DISCUSSION

Previous research on testing the impact of feedback training on children's handwriting performances has been encouraging. Although various feedback techniques have been used, the principle of social tracking, which involves both sensory and supplementary feedback, now seems to be of greatest interest. Consequently, the experimental program of the present study was developed and conducted in line with this kind of learning/instruction. During testing and treatment attention was paid to the accuracy and smoothness parameters in copying and writing. No training in fast writing was given, but Ss' speed-scores in writing were measured in pre- and post-test.

In one of our later studies (Søvik & Teulings, 1983) we suggested that dynamic social tracking should be preferred to CAI, especially with regard to children suffering from learning disabilities (deficient motor control). Results achieved from the present study seem to have confirmed this point of view. Ss in the D-group had a relatively greater increase of their accuracy-scores in copying and writing than Ss in the N-group, even though a significant increase of the accuracy-scores was found for all students who had taken the experimental treatments.

The absolute velocity curves of 'normal' and dysgraphic Ss were measured, analyzed, and interpreted to control progress in smoothness during the experiment. In general, more Ss in the E- than in the C-group seemed to have changed their writing pattern on account of the training program including exercises in finger/hand coordinations and smooth writing. Once again the dysgraphic Ss seemed to have had a relatively greater progress in developing a more smooth pattern of writing during the treatment sessions than had Ss in the N-group. However, conclusions should be drawn with care for several reasons. The testings and analyses were done with the word 'arkade' only, and the method of measurement and analysis used in the present study should be examined and tested more thoroughly before further research is being realized. To date, researchers have been in search of finding a satisfactory method for measuring and evaluating the smoothness parameter. So far, we think the absolute velocity curve is one adequate measure of smoothness/writing behavior. When data from our present investigation, like our 1983 study, indicated that feedback training can improve the writing pattern of a great many school children, there is evidence to state that homothetic transformation in time domain can be an organizational principle subject to training. Such training seems to take advantage of the principle of social tracking.

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Overview

The contributions in this Section admirably show the fertilization of the study of handwriting by insights gained in other disciplines such as systems theory, computer science, and biomechanics. The success of model building in this area not only had aesthetic or theorietical significance, but opened up possibilities of interaction of handwriting systems with other information processing systems. We began this Section with two studies that were less immediately concerned with practical aspects of handwriting research. Nevertheless, both studies considered handwriting in the wider contexts of motor activities of various levels of complexity or that of biomechanical system dynamics. Morasso analysized handwriting in the general context of trajectory formation, considering specific modelling and computational aspects, aiming at normalization and coding of cursive script. Normalization included time scaling, baseline compensation, slant compensation, and size scaling. Without a rigid hierarchy among them, motor activities were classified as a multiplicity of action paradigms, including muscle contractions, joint rotations, trajectories, and tasks. Covering complex trajectory formation patterns and handwriting, different elements of trajectory formation, including coordination, timing, and geometric transformations were considered with regard to motor activities of increasing complexity. A trajectory formation model was presented, based on the hypothesis of a kinematic planning of fundamental motor patterns.

Plamondon and Lamarche investigated the possibility of a modelization of handwriting from a systems approach. This study was based on the work of simulating handwriting with two pairs of mechanically coupled motors. The transfer function of the electromechanical system was used as a basis. When tested with the study of the transient response of the system and with dynamic synthesis of handwriting movements along one principal axis using a sequence of stimuli extracted from experimental data, a second order model was found to be unsuitable. Although there were inherent mathematical difficulties in estimating the parameters of the third order model, a third order model was better supported by a complete analysis of the transient response data. The systems approach provided insight into the transient and permanent responses of the biomechanical system.

The following three contributions concerned more practical tasks, including the automatic recognition of different types of handwriting on the basis of stroke build-up of the characters and words, signal processing techniques in handwriting research, and the employment of mathematic distance functions in predicting legibility. The paper by Tappert reviewed a system for handwriting recognition. The system has two components, a word segmenter and a word recognizer. Different levels of segmentation was required for different handwriting types. Training, updating, and recognition modes of operation were carried out by the system. Although it was conjectured that machine recognition of unconstrained handwriting was possible, prototypes representiing each alphabet character and some writer constraints were required at this stage. The author also discussed differences between a recognition system for Chinese and English, such that the units that correspond to prototypes for Chinese are characters and not letters.

Mamaari and Plamondon described a hardware set-up that can be connected to the output of a digitizer to obtain analog pentip position, velocity, and acceleration signals almost simultaneously. These analog signals can then be digitized at a convenient sampling frequency for computer data analysis. The electronic system was based on signal sampling and synthesis theory. A comparison between handwritten patterns and the corresponding static and dynamic representation of the analog pentip position signals showed an accurate match. The almost instantaneous availability of the pentip information was valuable for real time handwriting analysis and recognition.

From the vantage point of a computer scientist, Suen explored the distinctiveness of characters, including letters of the alphabet and Arabic numerals, measured in terms of ten distance functions. These included measures of similarities, dissimilarities, information, and matrix composition. Legibility measures of a large number of samples of these characters were obtained from subjects being presented these characters in tachistoscope conditions. Although these were some significant correlations between some of these ten measures themselves, there was no significant correlation between legibility measures and any of the ten distance measures. It was suggested that human recognition of handwritten characters was based on a complex process comprising not only combinations of distance measures, but also other cues accumulated from experience. This, of course, was a recognition that cognitive processes do not necessarily follow mathematic distance functions and reaffirmed the relevance of top-down processes in human information processing.

The final contribution in this Section, by Schomaker and Thomassen, examined the special problems associated with averaging handwriting signals beyond those of electrophysiological recordings. Specific problems were presented by the choice of the entities to be averaged, by the absence of external time-reference points, and by duration variability. The problem of stroke duration variability was dealt with by time-axis normalization prior to averaging. Examples of averaging at the stroke, letter, and word levels were presented. Results indicated that up to four letters can be averaged without noticeable distortion in the spatial domain. If care was taken in the selection of time references, time-axis normalization averaging was useful in movement analysis, pattern matching, and simulation of handwriting.

Graphonomics: Contemporary Research in Handwriting
H.S.R. Kao, G.P. van Galen, R. Hoosain (eds.)

UNDERSTANDING CURSIVE SCRIPT AS A TRAJECTORY FORMATION PARADIGM

P. Morasso

THE COMPUTATIONAL APPROACH

From the beginning of computer science, a few decades ago, similarities and dissimilarities between brains and computers have been a topic of controversial discussion. The comparison between brains and computers will become more earnest as computers are applied more and more to activities which were formerly considered essentially human. At the same time, the expectation of future "intelligent" computers and robots is stimulating a new approach to the study of intelligence and purposive behaviour, which is leading to a new science: we may call it "human information processing" or "anthropomorphic robotics" etc. In any case, the emphasis is on the computational structures which may lead to a certain level of performance.

If we compare brains and computers, at a first sight we may find more differences than similarities. For example, with regard to anatomy, i.e., the "hardware," the neurons and the microcircuits of present technology have very little in common in terms of physical characteristics, speed, type and number of inputs, types and number of outputs, etc., unless we consider them simply as basic information processing blocks. However, the same history of computer science teaches us that drastic technological revolutions do not affect essential computational concepts: a common unbroken line joins the Pascal or the Babbage machines (which were based on mechanical technology) to the electromechanical calculators of the last century, to the first electronic computer, the Eniac, which used the technology of thermoionic valves, to the different generations of modern computers, which exploit the tremendous potential of semiconductors. The story is obviously still in progress and we may expect newer and different technologies, without necessarily having to change the whole concept of "computer" and/or of "computation."

Also the basic arithmetic and information codes are probably different, for example there is no reason to think that the brain operates with binary numbers in the same way in which modern computers do. But also in this case, we may argue that the specific choice of a code (e.g., the binary code) is not essential: we might have computers with different codes and different types of information storage and still performing the same type of computational functions.

The difference between brains and computers is even more striking with regard to the "architecture." From what is known of the brain, we may suppose that it processes information in a parallel way, along millions of channels which, though rather slow, operate concurrently and asynchronously. On the contrary, existing electronic computers process information sequentially at a very fast rate. However, this kind of architecture (the so called von Neuman architecture) is far from being the ultimate design paradigm and, indeed, it is being lively challenged as the applications of the computer have expanded from pure data processing: image processing and robotics are examples of fields where new computational architectures are being theorized and implemented.

However, beyond such a long list of differences between brains and computers, and among different types of (existing or potential) computers, is there a level at which we can find similarities and permanent characteristics? If we think that the answer is yes, this is clearly the level of the task that they (brains and computers) perform, which is an "information processing task."

The independence of the "information processing tasks" from the specific hardware which implements them has been forcefully discussed by David Marr (Marr, 1982) in relation with human and computer vision. However, the same concepts which have been formulated by Marr are equally applicable, for example, to movement. In general terms, the goal of vision is to "make explicit what is in the world and where" and the goal of movement is to "navigate in the world and manipulate objects." Both tasks can be carried out using different types of hardware and different architectures: the computational approach consists of stressing the information processing aspects of intelligent behaviour abstracting it from specific hardware and architectures.

The computational approach, in our opinion, is not only a very useful epistemological tool for understanding intelligent behaviour, but it is a distinctive strategic characteristics of intelligence itself. For example, "picking up a banana" is a basic motor pattern which an intelligent actor should represent and program independently of the initial conditions which may characterize a specific "banana pickup," such as size, shape, position, orientation of the banana, initial posture, selection of supporting limbs and of the grasping limb, activation of specific groups of muscles, coordination among sets of joints, etc.. Similarly, the visual processing of optical data, such as the retinal image of a banana, cannot be reduced to a pure pattern matching, and it must be independent of the particular shape, color, position, orientation of a banana.

MUSCLES, JOINT ROTATIONS, TRAJECTORIES, TASKS

As pointed out in the previous section, "vision" and "movement" can mean many different things. Restricting ourselves only to "movement," it is possible to make the following examples of movement paradigms:

1. Muscles contractions without motion, e.g., isometric movements of one part of the body against another one or against an object, with the purpose of exerting a force, or regulating stiffness.
2. Rotations of a body part around a joint, e.g., rotations of the eye in the eyeball, of the head around the neck, or of the hand around a door-knob.
3. Trajectories of a body part, such as the hand, with regard to the body (e.g., in eating "the hand brings the food to the mouth") or with regard to the some object in the world (e.g., in handwriting the hand-held pen "traces a curve on a piece of paper").
4. Fundamental motor tasks, such as walking, where the main sub-task ("navigate the body in the world along a path") is performed concurrently with other instrumental tasks (such as "keep from falling" (which in turns require other and more specific sub-sub-tasks (such as "coordinate the legs and the arms" (which most likely will depend strongly on the specific "walking performance" (nature and shape of the terrain, type of shoes etc.))))).
5. Complex motor tasks, such as "assembly line work" or "dancing," where all the previous motor patterns may come into action, in different combinations and sequences.

Therefore, even if all movements end up eventually with patterns of muscular activities, they can be best "understood" in terms of rotations, trajectories or complex combinations of them, according to the type and the context of the motor performance: here "understanding" means different things, such as "analysing," "teaching," "learning," etc..

The "ecological" nature of perception has been strongly emphasized by Gibson (1979) and the same ecological concept has been extended to action, among others, by Reed (1984), and by Turvey and Kugler (1984).

The key aspect, from our point of view, is that "perception and action" are not uniquely determined by "afference and efference" but also by the flow of energy which links an actor and its environment. From this follows the theory of "direct perception" and "direct action," which opposes the conventional "retino-centric" or "musculo-centric" approach: on the contrary, it is suggested that perception and action are concerned mostly with the actual "direct" relations between the actor and the environment. Even if the direct approach has been contrasted to the computational approach (Ullman, 1980) as antagonistic, in our opinion the direct approach implies only a refusal of retino-centric or musculo-centric computations. On the contrary, the central role of the relation between the actor and the environment, which is emphasized by the direct approach, points out the predominance, for example, of kinematics with respect to dynamics, of solid modeling with respect to image processing, etc..

The previous considerations explain why muscle activity patterns are not appropriate to characterize movement, except for some very specific motor paradigms. Similarly, joint rotations are in most cases "internal events" far removed from the direct actor-environment interface (Bernstein, 1967). Head/eye movements, however, are a notable exception, which is worth considering in its own, also because it offers a good example of the stereotyped spatio-temporal patterns which might be used by the brain as basic building blocks of action synthesis.

EYE-HEAD MOVEMENTS FOR TARGET ACQUISITION

The movements of the eyes have the function of rotating the optic axis with respect to the head, in such a way that a visual target is either acquired or maintained in the central area of the retina. Therefore, in the case of the eyes "movement" means "rotation." The "target grasping" function of the eye movements is complemented by the movements of the head, which also have in this context the meaning of rotations.

From the mechanical point of view, eyes and head are a kinematic chain, one of the many which can be considered in the human body: the motion of the eye with respect to the environment is the sum of the eye rotation (with respect to the head) and of the head rotation (with respect to the environment) (Jones and Milsum, 1965). The function of the eye-head chain, as of other chains, is to relate in a desired way the last element of the chain (the eye in our case) with some feature of the environment. This implies a geometric mapping between "global" variables and "internal" variables. In general, this mapping is non linear, but this is not the case for the eye-head system. What is also special of the eye-head system is the vestibulo-ocular reflex (VOR), an automatic mechanism which drives the eye rotations in such a way to compensate for voluntary or involuntary head movements. The VOR is operated in feedforward from inertial sensors (the jsemicircular canals) which, at the same time, stabilize in feedback the position of the head in space. This kind of arrangement tends to cut the mechanical coupling of the eye-head chain allowing the brain to program movements of the eyes-in-space without bothering about the "disturbing" effect of the head motion. In general, dominating the mechanical coupling is the purpose of any controller of a kinematic chain.

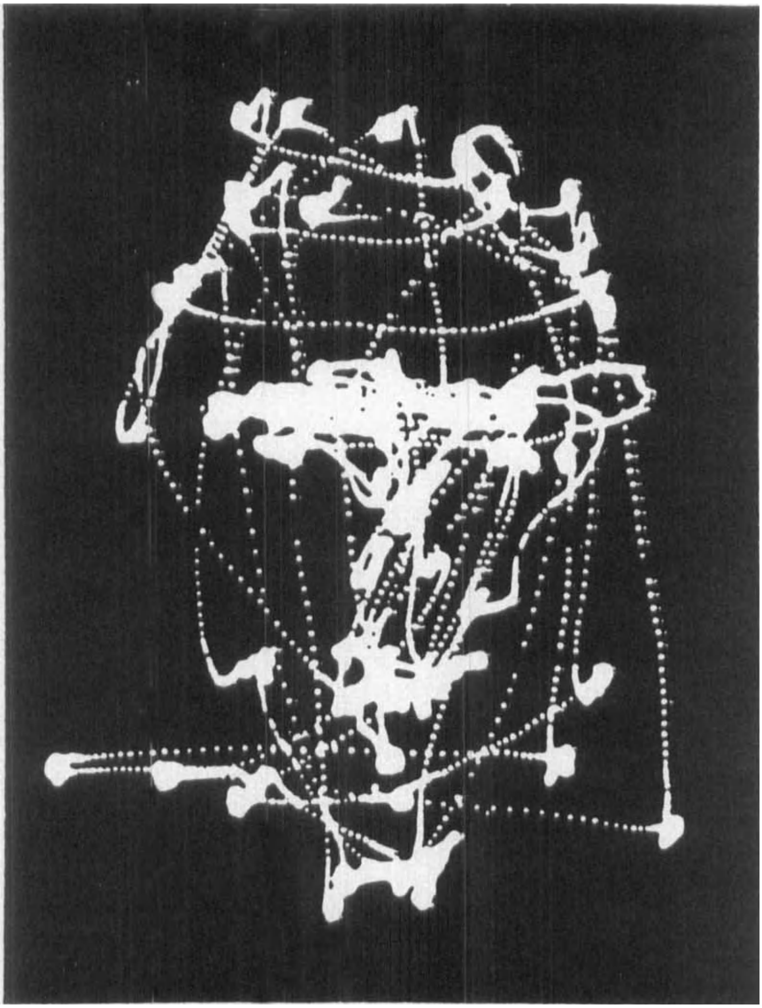
What is special about the eye-head chain, with respect to other chains such as the arm, is that the functional uncoupling is obtained through a measurement (the reafferent vestibular signal) instead of a patterned motor program, as it is more likely to happen in the case of arm movements. There are, of course, functional justifications for this special arrangement, related to the strategic role played by the vestibular organ in all the orientation matters, particularly those which cannot be pre-programmed in tasks of navigation. However, it is interesting to point out that the brain can also perform differently, in the more "standard" pre-programmed way, if the special vestibular sensor is not available: this was demonstrated by recording pre-programmed compensatory movements of the eye in labyrinthectomized monkeys, after a suitable period of recovery (Dichgans, et al., 1973). Thus, even if different from the other kinematic chains of the body for its mechanical structure and for its normal mode of operation, the eye-head system seems to have access to the same brain structures which allow to program in a coherent way all the degrees of freedom of a kinematic chain.

Let us now consider two interesting aspects of the eye-head coordination for their relation with the other kinematic chains of the body: one has to do with the shape of "eye-head trajectories" and the other with their temporal structures (we are considering here only the saccadic movements, which are analogous to the reaching/pointing/touching movements of the hand.

With regard to the shape of the eye-head trajectories in the exploration of the environment, they have been found to be approximately straight (see Figure 1). This result must be considered in relation with the complex non-linear mapping which exists between the lines of action of the eye/head muscles and the degrees of freedom of the eye (Robinson, 1982; Carpenter, 1977). In our opinion, this is one of the pieces of experimental evidence (as it is also argumented in the section on arm trajectories) which support the concept of "kinematic planning of fundamental motor patterns" on the basis of a "principle of smaller complexity of the representation."

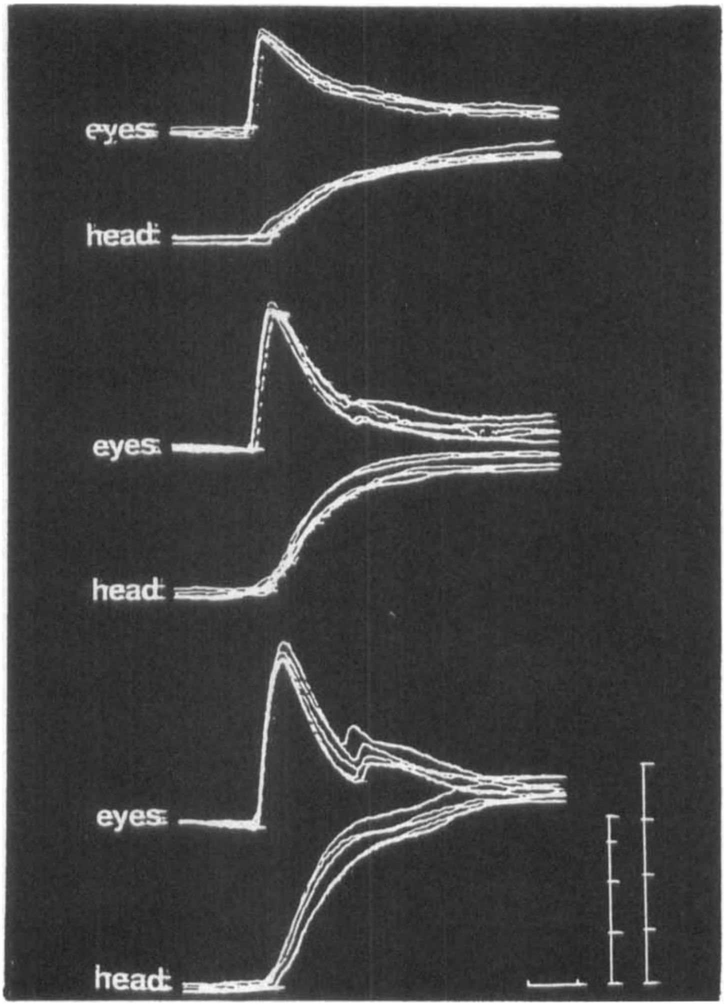
With regard to the temporal structure, it is well known that the eyes, differently from most other motor subsystems, are not characterized by an approximate isochrony, i.e., the duration of saccadic movements is not independent of the movement amplitude but it is a monotonic function (Robinson, 1964; Morasso, et al., 1973). There are reasons for both types of performance: the saccadic motor system is a servomechanism which operates at maximum speed and constant load, saturating the power output of the extra-ocular muscles. On the contrary, the neck or arm motor system is normally operated with a large power reserve, which allows to implement an "isochronous strategy" (see Figure 2). The advantage of isochrony, as it is also argued in the next sections, is the simplicity of synchronization of sequences of overlapped movements, a trick which allows to generate arbitrarily complex trajectories with stereotyped motion primitives (Figure 3 shows an example of a sequence of overlapped head saccades generated concurrently with a sequence of eye saccades). Even if eye and head exemplify

Figure 1 Trajectories of the eyes in scanning a picture of a face (Palmieri, et al., 1971).



two different temporal patterns, nevertheless it is worth noting the kind of "temporal matching" which exists between the duration of head movements (about half a second) and the refractory time of eye saccades (about a quarter of a second): in such a way, two saccades (a main and a corrective one) can fit into a single head saccade and a sequence of overlapped head saccades, such as those of Figure 3, can be nicely synchronized with a concurrent sequence of eye saccades in a coherent exploratory pattern.

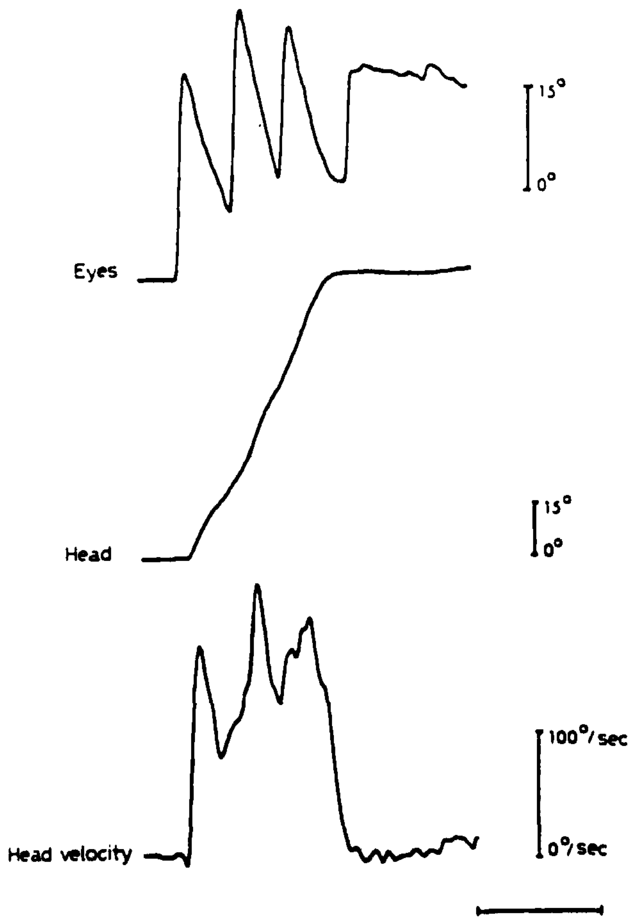
Figure 2 Timing of eye and head saccades of different amplitudes. Eye and head saccades during targeted movements start simultaneously. The duration of the eye saccades increases systematically with amplitude. The head saccades are substantially isochronous.



ARM MOVEMENTS FOR TARGET ACQUISITION

The acquisition of targets is one of the basic visuo-motor functions. From the visual point of view, it entails coordinated eye-head movements which bring the optic axis of the eyes onto the target while keeping the eyes close to mid range. From the manual point of view, target acquisition means to

Figure 3 Eye-head scanning movements. Note modulation of head velocity synchronous with saccadic eye movements (time calibration: 500 ms) (Bizzi, et al., 1972). Note the temporal matching between the duration of the head movements and the delay of the eye saccades.



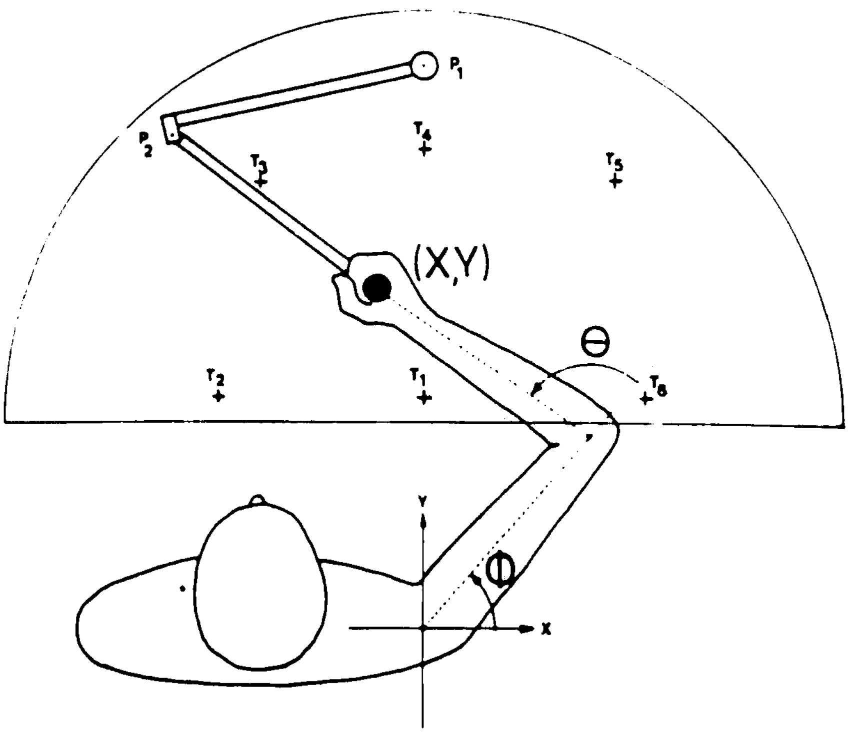
generate a coordinated set of movements which carry the hand from an initial position in space to the target position. The global structure of such a motor pattern depends on the position of the target: if the target is close enough, then only movements of one arm are functionally necessary, otherwise movements of the trunk and legs are required, possibly preceded by locomotion movements. On the other hand, also in the case of simple movements of the arm a large number of other motor subsystems are called into action in order to guarantee postural stability (Polit and Massion, 1979).

Therefore, when we speak of "targeting" we mean in general a complex array of concurrent processes. However, if we make the hypothesis that such processes are independent to a large degree and are coordinated on a different computational level, it is still meaningful to focus our attention only on the arm movements induced by targeting tasks in which the distance of the targets is at arm-length. Let us make the further hypothesis that the fingers and the wrist are restrained from moving as well as the trunk.

In the two-joint movements that we are considering, a "decomposition" can be observed if we ask (or we force) a subject to move only one joint at a time, e.g., the elbow first and then the shoulder: The trajectories of the hand that we observe are two circular arcs. If the two joints are rotated together, then an infinite variety of shapes can be obtained, strictly dependent upon the synchronization among the two joints.

In targeted movements, only the initial and final positions of the arm are specified by the task: The trajectory which joins them is a choice of the Central Nervous System. In order to investigate such a choice, experiments have been performed (Morasso, 1981) in which human subjects were instructed to point one hand to different visual targets which were randomly sequenced in a plane (Figure 4). The results of the experiments are presented in Figures 5 and 6. Figure 5 shows the spatial trajectories of the hand and Figure 6 shows the time course of the joint angular position, joint angular velocity and hand tangential velocity, for four different movements. Joint angular velocities (frame 3, second row) for these different movements exhibit quite different patterns; some joint angular velocities are single peaked and some are double peaked (which means inversion of the joint motion). The four movements of the figure exemplify all the four possible combinations (single peak/double peak) for the two joints. In contrast, the tangential hand velocity for the different movements has a single peaked curve (an acceleration phase, followed by a deceleration phase) that varies very little in shape among the movements. The duration of the different movements was rather constant, independent of the movement distance and of the joint angular pattern. This kind of "isochrony" of arm targeted movements mirrors the behaviour of head targeted movements and is in accordance with early observations (Bryan 1892, Stetson and McDill 1923).

Figure 4 Arm targeted movements in the plane. (fi,theta) are the intrinsic coordinates. (x,y) are the extrinsic coordinates. (T1,...T6) are the visual targets used to elicit the targeted movements (Morasso, 1981).



Furthermore, the trajectories of the hand appear to be approximately straight, a finding corroborated by other investigations (Abend, et al. 1982; Hollerbach and Flash, 1982), also in the case of three-dimensional movements (Morasso, 1983). This finding may be expected on the basis of casual observation of human behaviour. It is of interest because the straight hand movements result from the interplay of the rotation of each of the involved joints (elbow and shoulder in our case): Curved or sinuous movements would result if the two degrees-of-freedom were not perfectly coordinated.

Summing up, the experimental findings on arm targeted movements reveal that invariant features of that patterns are (i) the bell-shaped velocity profile of the hand, and (ii) the (rough) straightness of the hand trajectory. On the contrary, the joint rotation patterns do not show significant invariances: they are more variable and, therefore, more "complex."

Other researchers have investigated the opposite possibility, looking for regularities and invariances in the joint rotation patterns, for targeted

Figure 5 Typical trajectories (for three subjects) of the arm in the plane (the sampling time was 100 samples/sec.) (Morasso, 1981).

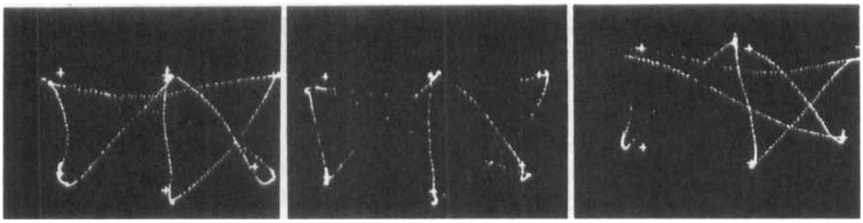
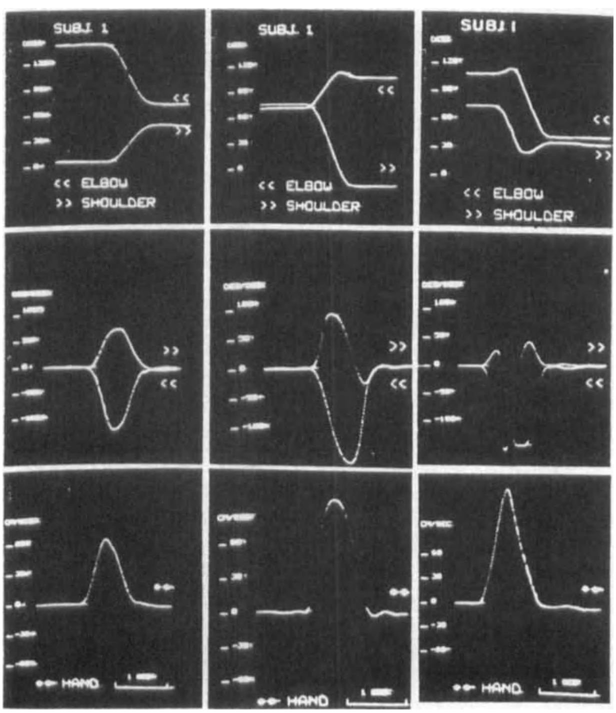


Figure 6 Intrinsic and extrinsic patterns during arm targeted movements. Top row: joint rotations. Middle row: joint angular velocities. Bottom row: hand linear velocity. The column row corresponds to a radial movement (from a position close to the shoulder to a position far from it). The central column corresponds to a movement from a position far-left to a position far-right. The right column corresponds to a movement from a position close-left to far-right (Morasso, 1981).



movements in a vertical plane (Soechting and Lacquaniti, 1981, Lacquaniti and Soechting, 1982). However, the apparent straight lines in joint space that they found have been demonstrated by Hollerbach and Atkeson (Hollerbach and Atkeson, 1985) to be artifacts of movement kinematics near the workspace boundary.

In relation with the trajectory formation process, it is worth addressing the issue of complexity, which was outlined above, on passing. Suppose that we take as a measure of complexity of a signal the width of its frequency spectrum. Then, if we consider the joint rotation signals which correspond to the recorded hand targeted trajectories, we can say that the intrinsic representation of the targeted movements is "more complex" than the extrinsic representation of the same movements.

The brain controls the movements generating a set of efferent signals which are certainly "closer" to the intrinsic representation than to the extrinsic one. Furthermore, the intrinsic representation is the input to the non linear geometric transformation which yields the extrinsic representation as its output.

The output of a non linear mapping is in general "more complex" than its input, because more frequency components tend to be created, unless the input is "crafted" in such a way that some of the frequency components of the spectrum are mutually cancelled out. It appears that such "crafting" takes place in many types of motor performance. This can only mean that the "motor controller" which generates the complex patterned efference is dominated by a "motor planner" which formulates and shapes a trajectory plan "directly" in terms of the extrinsic representation. As already anticipated in the previous section, we would like to call this the principle of smaller complexity.

COMPLEX TRAJECTORY FORMATION PATTERNS

Since targeted hand movements reveal a tendency of subjects to produce straight hand paths, it is interesting to study motor paradigms in which the subjects are required to program not only the total extent of the movements but also their "shape". This is the case, for example, in (i) targeted movements which are constrained by an obstacle or by a guiding path (we may call them "constrained targeted movements"), in (ii) "hand gestures" which produce hand trajectories of different shapes, and in (iii) handwriting movements. Let us now consider in more detail these movement classes.

Constrained Targeted Movements

The movement strategy used by subjects who had been instructed to reach a target on a curved path were investigated in depth by Abend, et al. (1982). Three experiments were conducted where trajectories of the hand were recorded in the horizontal plane. In the first, the subject was instructed to move his hand to the target by way of curved paths; in the second, he was told to move his hand to the target along straight or curved guide paths; and in the third, he moved his hand around an obstacle to reach the target.

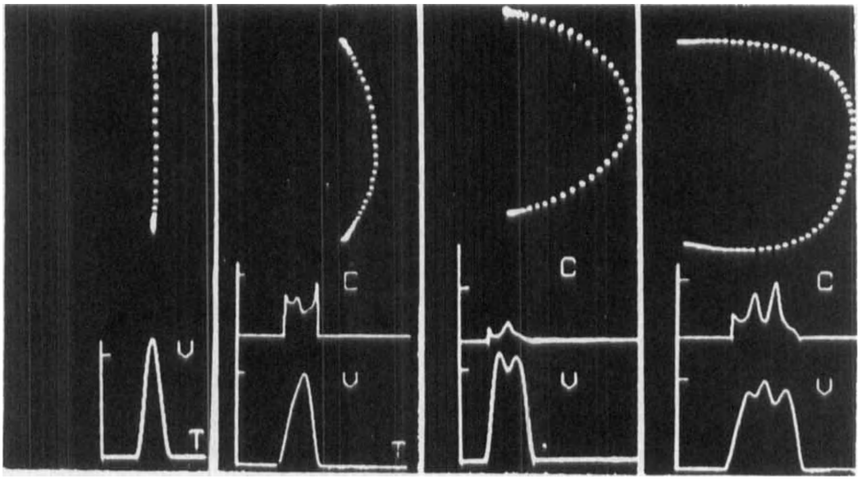
Figure 7 shows a typical series of movements, between the same two targets, characterized by an increasing deviation from the straight line. For each movement, the path of the hand, the time course of the hand speed and the path curvature are presented. The first movement is a "pure targeted" movement, with a near-straight (i.e., zero curvature) path and a bell-shaped velocity profile. In the curved movements, the velocity profile is no longer bell shaped and it exhibits a characteristic segmentation. Furthermore, the curved paths appear to be composed of a series of gently curved segments which meet at more highly curved regions (consider, for example, the two peaks of curvature of the fifth movement of Figure 7 which separate the three segments of the hand path). Remarkably, the peaks in the curvature profile correspond temporally with the speed valleys.

The segmented appearance of curved paths and its correlation with the structure of the speed were also found for different kinds of geometric constraints added to the main targeting task: (i) when subjects attempted to mimic constant curvature guides, (ii) when they tried to reach a target avoiding an interposed obstacle, or (iii) when the position of the target was changed during the execution of the targeted movement. Another common finding was that the modification of the speed profile (from straight to curved movements) was consistently accompanied by an increase of the movement duration, independent of the path length.

A segmentation of the speed profile can also be observed in targeted movements for other types of constraints: (i) when the subject approaches the target in a time deliberately longer than the self-paced movement duration (usually around half a second), and (ii) when the required accuracy (the ratio between movement length and target size) is great enough. In particular, the latter finding must be compared with the classic observation by Fitts (1954) that the duration of movements to a small target increases with the movement accuracy.

Both findings are consistent with the notion that the basic motor primitive is a spatio-temporal unit with a rather fixed duration, with a stereotyped bell shaped velocity profile, and with a rather constant percentual accuracy; within such a framework, the segmentation of the velocity profile in the previously mentioned paradigms can be interpreted as the attempt of the subjects to produce a constrained trajectory by means of a chain of primitive targeted movements characterized by low curvature.

Figure 7 Targeted movements along curved trajectories. Sampling frequency: 50 Hz. Velocity profile (V: calibration 500 mm/s). Curvature profile (C: calibration 0.008 1/mm). Time calibration: 3.5 s. (Morasso and Mussa Ivaldi, 1982).



Hand Gestures and Handwriting

In the constrained targeted movements considered in the previous section, the deviation from the spontaneous nearly straight trajectories comes about as a result of some additional type of "external" constraint. In hand gestures (including hand drawing) and in handwriting, the hand path is not produced in accordance with an "external" constraint but it is derived from some kind of representation of the "shape" that is imagined and/or planned (which we may consider an "internal constraint").

Let us now consider some experimental data on hand gestures and handwriting (Morasso and Mussa Ivaldi, 1982). Figure 8 — left shows hand gestures which produce trajectories with a varying degree of "roundness." Figure 8 — right shows hand gestures whose trajectories exhibits different types of inflection points. Figure 9 shows the repetition of the same pattern shape, while keeping the same pattern size, and the effect of systematically varying the pattern size, while keeping its structure. Figure 10 shows two examples of handwritten patterns.

Arm body/coordination is required when the hand trajectory exceeds the arm length, for example when writing on a blackboard. Figure 11 shows an example of this paradigm, displaying the trajectories of the hand and of the shoulder. The motor patterns of the hand are quite similar to those which are usually recorded in handwriting studies. The trajectories of the shoulder

Figure 8 Left: closed trajectories of different "roundness". Right: Trajectories with different types of inflection points. Sampling frequency: 50 Hz. Velocity profile (V: calibration 500 mm/s). Curvature profile (C: calibration 0.04 1/mm left, 0.008 1/mm right). Time calibration: 2.6 s. (Morasso and Mussa Ivaldi, 1982).

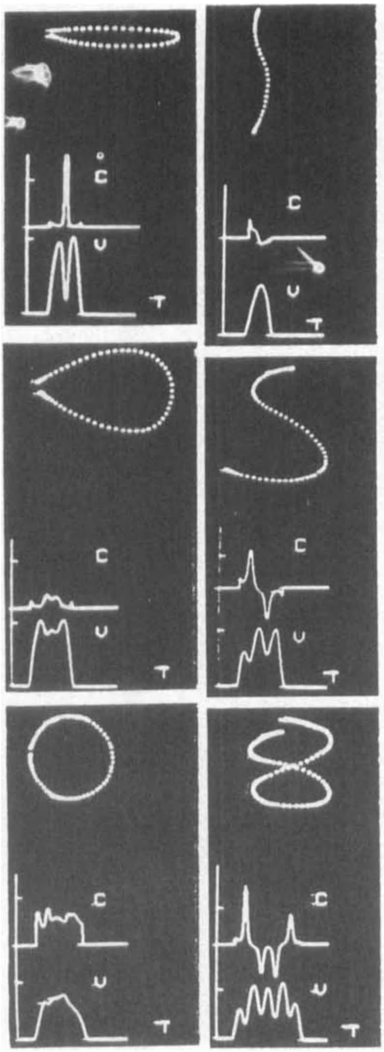


Figure 9 Top: repetition of the same pattern shape with a constant size. Bottom: repetition of the same pattern shape with an increasing pattern size. Sampling frequency: 50 Hz. Velocity profile (V: calibration 500 mm/s). Curvature profile (C: calibration 0.2 1/mm top, 0.008 1/mm bottom) (Morasso and Mussa Ivaldi, 1982).

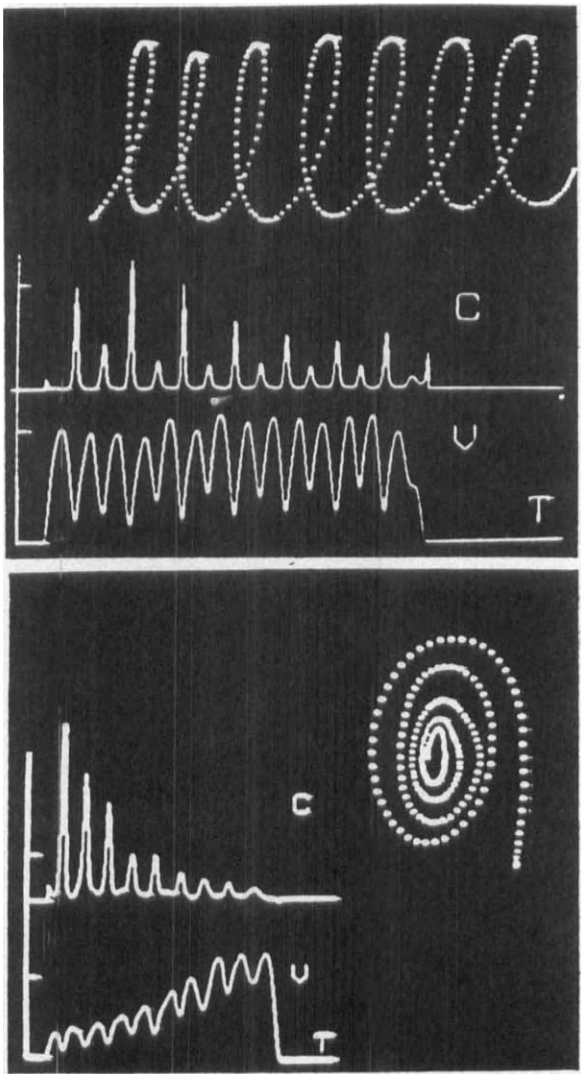
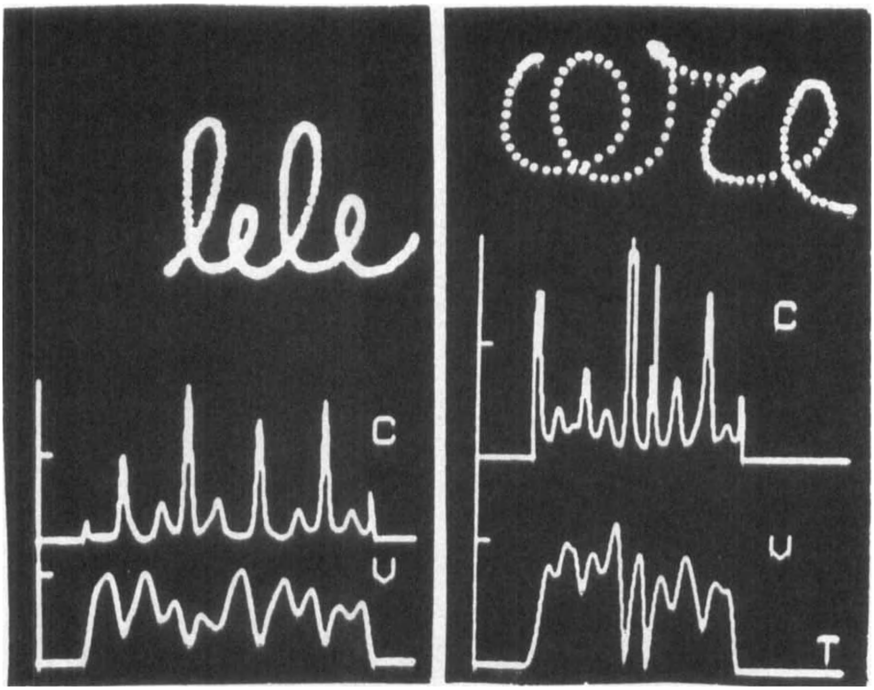


Figure 10 Handwritten patterns. Sampling frequency 50 Hz. Velocity profile (V: calibration 500 mm/s). Curvature profile (C: calibration 0.008 1/mm). Time calibration: 4.5 s. (Morasso and Mussa Ivaldi, 1982).

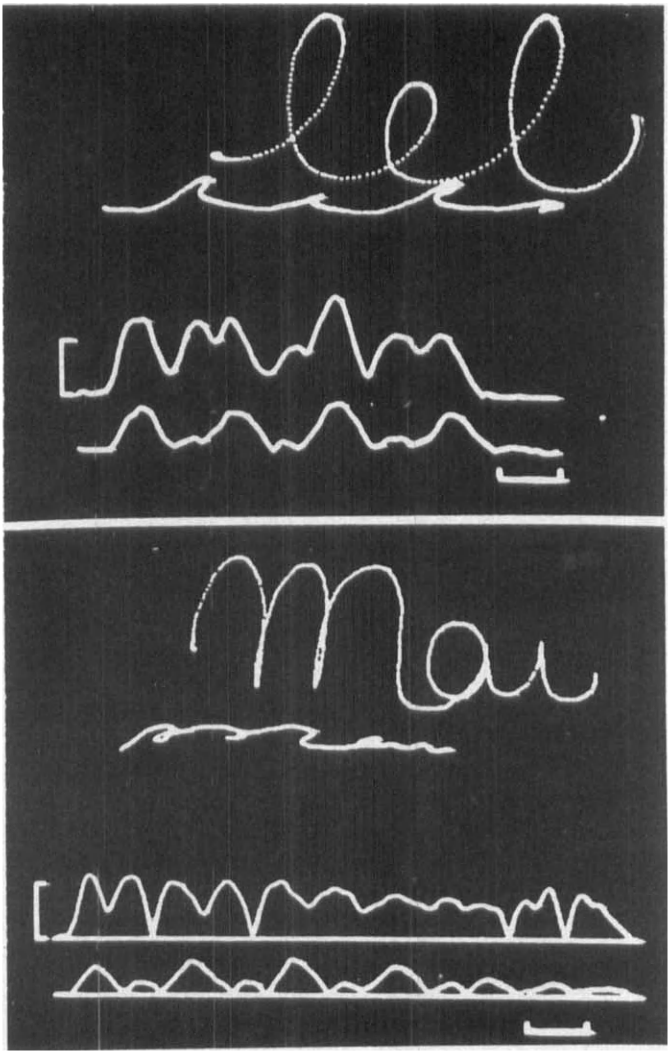


are a more or less distorted version of the hand trajectories and are influenced by the concurrent stepping movement. In any case, it is remarkable that the subjects, with apparent ease, can generate the same "extrinsic" movements in face of a widely different "intrinsic" implementation. This is another argument in favour of the central representation of hand trajectories.

The most important finding is that all the patterns share a global common structure. In particular let us point out the following elements:

1. The curvature peaks are strongly correlated with the segmentation of the velocity profiles.
2. The curvature peaks are rather uniformly sequenced in time, independently of the sharpness of the trajectory bending (a finding which is germane to the approximate isochrony of unconstrained targeted movements).
3. The sharper the trajectory bending, the greater is the concurrent slowing down of the hand (this fact is compatible with the simple vector addition of sequences of motor patterns with a bell-shaped velocity profile).
4. The above regularities are the necessary basis for producing the size invariant performance of Figure 9-bottom.

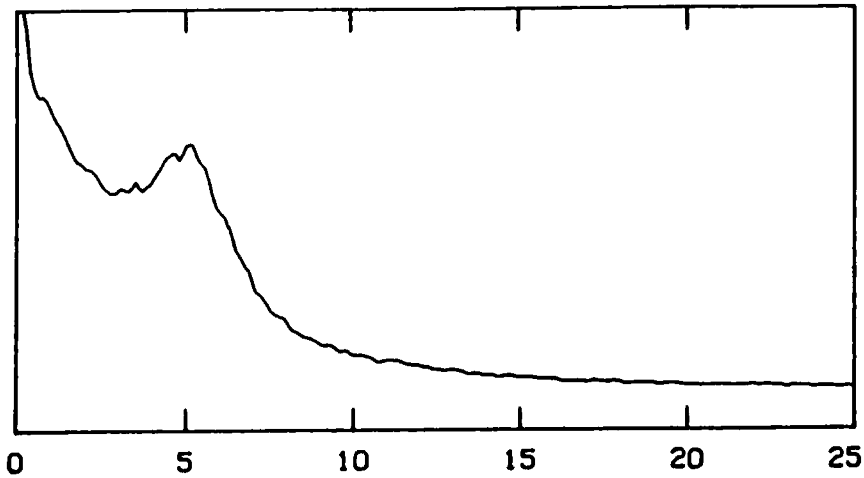
Figure 11 Arm/body coordination: handwritten patterns on a (vertical) blackboard. The top trajectory is drawn by the hand. The bottom trajectory is drawn by the shoulder while moving the body (sampling frequency: 50 Hz). The extent of the trajectories is about two meters. The two curves represent the tangential velocity of the hand (the top one) and the tangential velocity of the shoulder (the bottom one). Vertical calibration: 1.2 m/s. Horizontal calibration: 1 s.



5. Handwriting does not seem to be characterized by special spatio-temporal structures, as far as the trajectory formation performance is concerned.

Since hand gestures and handwriting produce complex signals (x=x(t), y=y(t), together with their derivatives), spectral analysis is an appropriate analysis tool to single out structural properties of the generation process. Figure 12 (Teulings and Maarse, 1984) shows the average amplitude spectrum of the velocity time functions of a large set of handwriting movements.

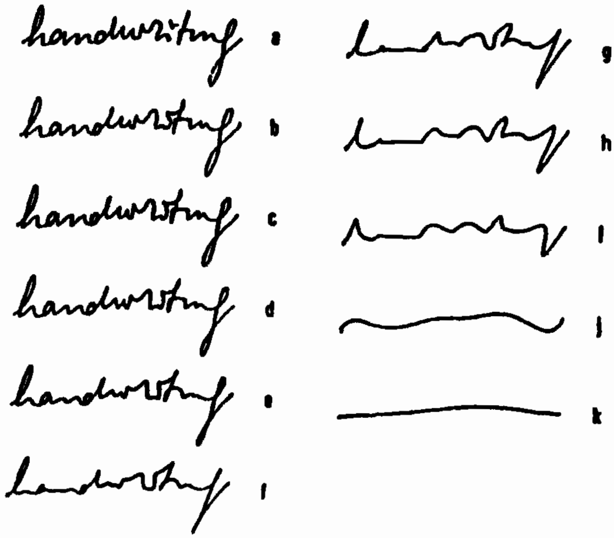
Figure 12 Average amplitude spectrum of the velocity time functions of a large set of handwriting movements. Horizontal scale: Hz (Teulings and Maarse, 1984).



The spectrum has a peak at about 5 Hz and it vanishes after about 10 Hz. Consider now targeted movements: they have bell shaped velocity profiles of about 400-500 ms duration and therefore the corresponding spectra will also be roughly bell-shaped with a frequency band of about 2-2.5 Hz. The handwriting composite spectrum reveals an underlying periodic mechanism with an average period of about 200 ms (the mild sharpness of the peak suggests some fluctuation in the generation rate): in any case, such a peak can be related to the "isochrony" of targeted movements. Furthermore, the energy of the spectrum between 5 and 10 Hz can be interpreted as being due to the "amplitude modulation" of the quasi-periodic generation mechanism which tends to localize energy in the spectrum around the 5 Hz "carrier." Figure 13 (Teulings and Thomassen, 1979) shows the result of filtering the Cartesian components of a piece of handwriting with a low pass filter of decreasing cutoff frequency. A 10 Hz cutoff frequency leaves the trajectory unaltered and a 5 Hz frequency still preserves the basic shape of the trajectory; it is only below 2.5 Hz that most of the trajectory shape is lost.

All together, the indications which are provided by the frequency analysis of handwritten signals are compatible with the notion that complex trajectories are generated by a quasi periodic mechanism which uses, as primitive elements, trajectory segments with spatio-temporal characteristics similar to the targeted movements.

Figure 13 Effect of low pass filtering on handwriting signal. (a): original written trace. (b): digitized trace (sampling frequency 200 Hz). (c to k): low pass filtering with cut-off frequencies of 10,7,6,5,4,3,2,1,.5 Hz, respectively (Teulings and Thomassen, 1979).



MODELING TRAJECTORY FORMATION

We have seen different motion paradigms, from targeting to hand gesturing, which all result in the generation of planar or spatial trajectories of varying degrees of complexity. The hypothesis that is formulated in this section is that different paradigms of trajectory formation share a common generation mechanism. Let us list the specifications that we ask the model to fulfill:

1. It is directly expressed in terms of extrinsic instead of intrinsic coordinates.
2. It must produce smooth trajectories.
3. It must be powerful enough to produce any kind of shape (a requirement of completeness);
4. It must produce the type of segmentation which characterizes human movements.
5. It must be general, i.e.,it must be applicable in a uniform way to targeted movements as well as to handwriting.

A promising approach for fulfilling these requirements is provided by the family of methods which are used in computational geometry and computer graphics (Faux and Pratt, 1979) for generating Parametric Composite Curves. A parametric representation of a curve, in general, is given as a vector (in 2D or 3D space) expressed as a function of one independent variable. In our case, since we are considering movement trajectories, it is appropriate to use time as the independent variable:

(1) $r = r(t)$

which corresponds to a couple of scalar functions in the case of planar movements

$$x = x(t) \qquad (2)$$
$$y = y(t)$$

or to a triplet of functions in the spatial case

$$x = x(t)$$
$$y = y(t) \qquad (3)$$
$$z = z(t).$$

A parametric composite curve is a curve in the form (1) which is obtained by means of composition, i.e., by joining simpler curve segments. Therefore, we have three topics to emphasize: (i) segmentation, (ii) nature of segments, and (iii) composition.

As regards segmentation, the composition mechanism implies a discretization of the time axis as a sequence of time instants ("knots" or "breakpoints" in the terminology of spline functions) which mark the subdivision of the overall curve into composing segments. Therefore, one of the reasons for choosing parametric composite curves as possible models of trajectory formation is that they imply "segmentation" in a natural way.

The kind of curved segments which are mostly used in computer graphics are polynomial functions of time, because they have attractive mathematical properties (it is easy to compute derivatives, the family of polynomial curves of a given order is a linear vector space, etc.).

In order to join in a smooth way two consecutive segments, it is necessary that at the "breakpoints" the final values of a number of time derivatives of the previous segment coincide with the initial values of the corresponding derivatives of the following segment. For example, in the case of cubic segments the "smoothest" composition is obtained when continuity is guaranteed up to the second time derivative (which means also continuity of curvature). The piecewise polynomial curves which provide this type of "smoothness" are known as "spline" curves (cubic splines when the segments are cubic polynomial functions of time). Algorithms exist (de Boor, 1972) for computing the coefficients of a spline curve (i.e., the coefficients of each polynomial segment) on the basis of a set of interpolation points and of the choice of boundary conditions (in our case, the natural boundary conditions are that the first time derivative must the null at the beginning and at the end).

The algorithms which perform such computations are not "incremental," i.e., they require the advance knowledge of all the interpolation points and therefore are not well suited to carry out a trajectory formation task.

This drawback can be overcome by using a special kind of spline function: the B-spline. The B-spline function is a spline which is null before a given breakpoint, is non zero over the shortest time span and then goes back to zero. It turns out that the time span extends over a number of consecutive breakpoints equal to the polynomial order plus one (Figure 14A) and the function is smoothly bell-shaped.

For a sequence of m breakpoints there are m−4 cubic spline functions defined in such a way (Figure 14B) and for each time instant, except for the initial two and the final two time spans, there are 4 non null cubic B-splines. In order to maintain the same degree of overlapping on all the time spans, the above definition of cubic B-splines is completed with three additional couples of cubic B-splines: two are defined on three time spans, two are defined on two time spans, and two on one time span (see Figure 14C). Therefore, for a set of m breakpoints, the extended set of cubic B-splines contains m−4+6=m+2 functions. It can be shown that this extension is equivalent to adding three breakpoints coincident with the initial one and three breakpoints coincident with the final one. While the "internal" B-splines are maximally continuous at both ends, the "boundary" B-splines exhibit an increasing degree of discontinuity at one end (the left end for the initial B-splines and the right end for the final B-splines).

The purpose of the extension described above is to have 4 cubic B-splines active for each time span. Furthermore, the amplitude of the B-spline functions is normalized in such a way that the sum of all the active B-splines, for each time instant, is identically equal to one. The practical importance of B-spline functions is due to the property that any spline function of a given order, defined on a given set of breakpoints, can be expressed as a weighted sum of the B-spline functions of the same order, defined on the same extended set of breakpoints:

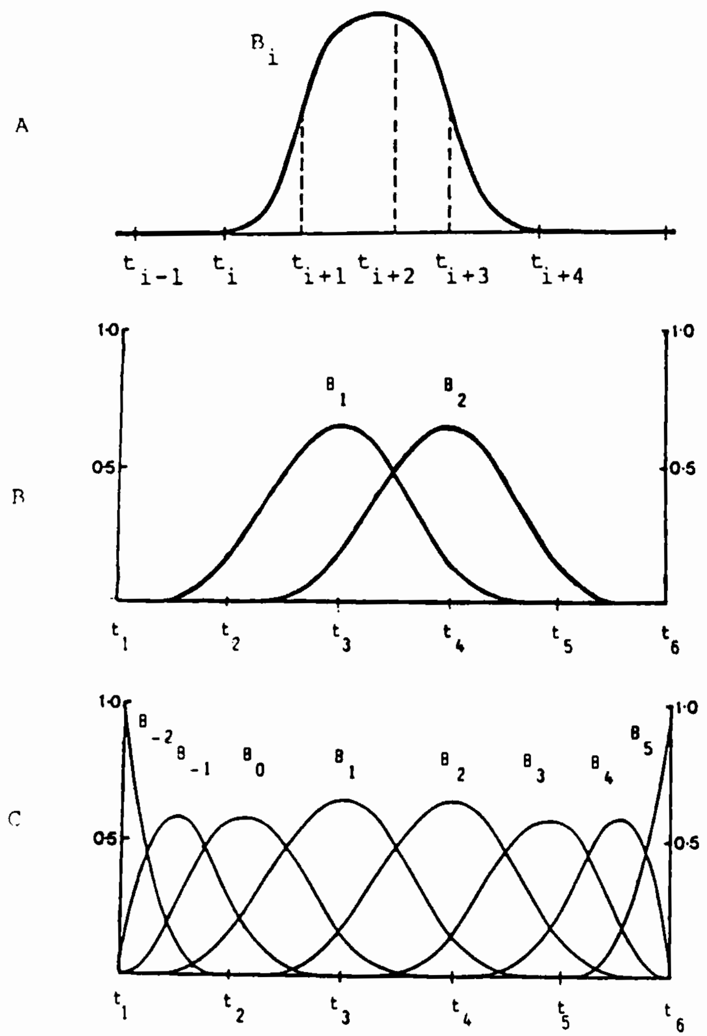
(4) $s = s(t) = \text{Sum}_j\ c_j\ B_j(t) \qquad j=-2,\ldots,m-1$

The coefficient of the B-spline expansion are not interpolation values (except for the initial and the final one). They are "guiding values" which "attract" the shape of the trajectory.

In the framework of a B-spline representation, a trajectory is formed by choosing the guiding points. A significant characteristic of the representation is that it is "local" (a modification of one of the guiding points affects the shape only in the time spans where the corresponding B-spline is non zero) and "incremental," i.e., the trajectory can be generated "on-line" specifying new guiding points or changing pre-planned sequences of guiding points.

The expansion (4) is directly applicable to spline functions. If we wish to

Figure 14 Cubic B-spline functions. A: standard cubic B-spline (its support is limited to four time intervals; note the convention of using the same index to indicate a B-spline and its initial breakpoint). B: standard cubic B-splines defined on a set of 6 breakpoints. C: extended set of B-splines on the same set of breakpoints, which takes into account the border effects (note that this kind of extension guarantees that four B-splines are active for each time interval and that their sum is identically equal to one).



apply it to parametric spline trajectories the only difference is that the guiding values are not scalars but are vectors (in two or three dimensions, depending whether we are dealing with planar or spatial curves):

(5) $r = r(t) = \text{Sum}_j\ p_j\ B_j(t) \qquad j=-2,\ldots m-1$

where the pj's are the guiding points of the trajectory. In the B-spline representation of a trajectory these points play an "absolute" role, i.e., they specify attracting points in space which influence the shape of the trajectory: in the case of cubic splines, for example, the relation (5) specifies that at each time instant only four of these points attract simultaneously the trajectory and at each breakpoint there is a discrete switching of the quadruplet.

However, it is possible to conceive the trajectory formation process in a complementary "relative" way, i.e., in terms of directions related to couples of consecutive guiding points. This approach leads to the definition of another set of basic spline functions: the S-splines (Morasso and Mussa Ivaldi, 1982). While B-splines are bell-shaped piece-wise polynomial functions, the S-splines are step-shaped piece-wise polynomial functions (see Figure 15). The active part of cubic S-splines is only three time spans (instead of four) and from this follows that at any time instant only three S-splines are simultaneously active. Spline functions (and spline curves) can be represented as an expansion in terms of S-splines in a similar way to the expansion (5) which uses B-splines:

(6) $r = r(t) = p_{-2} + \text{Sum}_j\ (p_j - p_{j-1})\ S_j(t)\ j=-1,\ldots m-1$

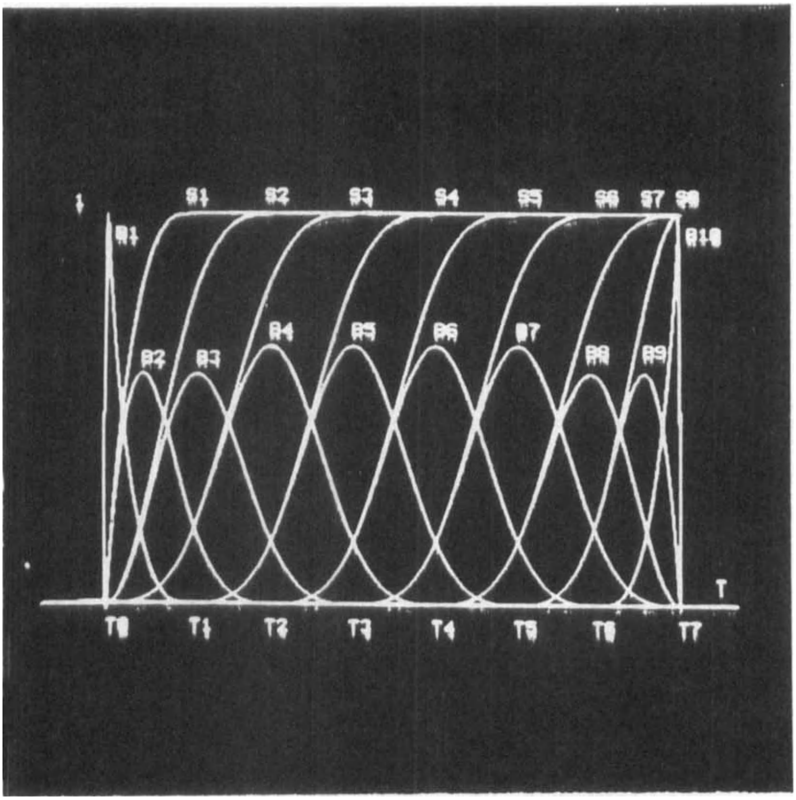
The S-spline representation is "relative" (instead of "absolute") because the trajectory formation process implied by (6) is characterized by "guiding vectors" (instead of "guiding points"). In particular, (6) can be interpreted as the vector addition of primitive straight movements ("strokes" in the motor terminology) directed along the guiding vectors, each of which is generated with a bell-shaped velocity profile and with a time shift among consecutive strokes characterized by the fact that at each time instant three of them are simultaneously active.

Trajectory and Cursive Script Coding

A "smooth" trajectory (or a curve in general) is naturally segmented by the points of minimum radius of curvature (or curvature peaks). The segments delimited by two of such consecutive points ("segmentation points") have a stereotyped shape: they are either C-shaped (if the curvature has the same sign at both ends) or S-shaped, in the opposite case.

In order to fit an experimental trajectory, it is possible to fit each segment, after the segmentation points have been estimated. Then, the shape of the

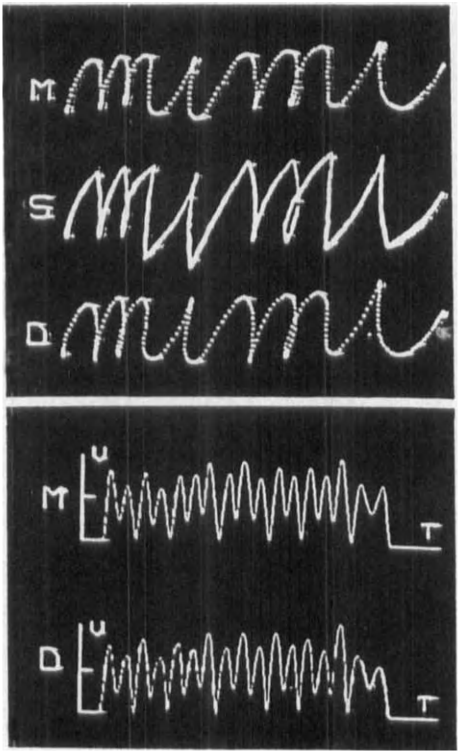
Figure 15 **B-splines and S-splines defined over a set of 8 breakpoints.**



curve segments can be accurately reproduced if we know the local behaviour of the trajectory at the segmentation points[1].

In particular, we can estimate a certain number of derivatives at these points (e.g., the zero, first, and second order derivatives) and then we can compute a B-spline or S-spline representation which satisfies such constraints. Figure 16 shows an example of curve fitted in this way. However, even if this kind of representation allows an accurate reproduction of the recorded trajectory, it is not yet a satisfactory model of trajectory formation for at least two reasons: (1) it is limited to straight strokes; (2) it requires that three strokes are always active simultaneously. On the contrary, there is ground to think that curved strokes, as well as straight strokes, are primitive movements in the motor repertoire and that no more than two strokes are simultaneously active.

Figure 16 Trajectory fitting with a S-spline representation. (B1,. . .,B10): breakpoints. (S1,. . .S11): S-splines. (G1,. . .,G11): guiding points. The two small circles identify the segmentation point.



In order to meet these requirements, it is possible to rearrange the representation given by (5) or (6) by observing that, if we subtract two strokes (the initial and the final one) from the set of linear guiding strokes, we obtain a number of strokes which is a multiple of 3. Each triplet of linear strokes generates a curved stroke ci:

(7) $c_i(t) = p_{i-1}S_{i-1}(t) + p_iS_i(t) + p_{i+1}S_{i+1}(t)$

with a bell-shaped velocity profile.

Linear strokes are identified by 2 parameters (direction and length) whereas curved strokes are identified by 6 parameters (2 have the same meaning, 2 are related to the "roundness" and 2 to the "skewedness" of the stroke). The S-spline representation (6) can then be re-written as a curved stroke representation:

(8) $r = r(t) = \mathrm{Sum}_i\, c_i(t) + p_{\mathrm{initial}}$ $i=1,2,\ldots$

which says that, in general, a complex trajectory can be formed by a process which generates sequences of curved segments (with a stereotyped velocity profile and with such a timing that no more than two strokes are simultaneously active) and composes them additively.

It must be stressed that the representation (8) is formally equivalent to the representations (6) or (7), but it better captures the structure of the human trajectory formation process.

Handwriting is a special type of trajectory formation paradigm which is characterized by the fact that the generated trajectories are not constrained in a "physical" way but in a more abstract "propositional" way; for example, the "picking up of an object" implies to plan a trajectory which drives the hand to a specific position in space with an appropriate orientation determined by the shape and location of the object, whereas the "cursive script" is the motor translation of a symbolism. As a consequence, in cursive script analysis it is significant to consider special trajectory formation concepts which are irrelevant in most other motor tasks. For example, since the Greek-Roman families of languages are characterized by a left-to-right organization, it is natural, in this case, to consider the concept of a baseline as the ideal line which marks the progress of letters into words and of words into sentences. The baseline, according to the acknowledged cursive script conventions, is supposed to be straight and horizontal, but the use of cursive script as a communication medium requires a large tolerance on the actual shape and orientation of the baseline, provided that it is smooth and slowly changing, at least at the word level.

The baseline provides one ideal axis for the trajectory formation task associated with handwriting; the second ideal axis can be chosen orthogonal to it, so identifying a natural system of reference. Ideal cursive script shapes are defined in the natural system or reference, together with "attributes" of the composing elementary shapes: for example, in the following definitions ("a long straight stroke down to the baseline" or "a short narrow loop above the baseline") "straight stroke," "narrow loop" are (parametrized) primitive shapes oriented in the natural reference, "short," "long" are size descriptors which have a relative meaning for the overall script, "above," "down" are positional descriptors with respect to the natural system of reference.

The same reasons of robustness which force the community of readers/writers to tolerate a variability in the baseline are good enough for accepting a non orthogonal system of reference, where the obliqueness (the slant) may be due either to mechanics (the use of two oblique degrees of freedom) or to cognitive aspects (the choice of a particular writing style) or to both (i.e., it is reasonable to think that writers tend to adopt writing postures in such a way that the resulting functional degrees of freedom match the desired slant).

Summing up, in modeling handwriting as a trajectory formation task, it is necessary to separate two distinct aspects: (1) global aspects which have to do with the natural reference system and are captured by the notions of baseline, slant, size, and (2) structural aspects, which are captured by the (arbitrary/individual) choice of primitive formal elements used to construct allographs.

Therefore, cursive script coding, which is a prerequisite for cursive script understanding, requires to express separately the two types of aspects. From the point of view of analysis, this means to identify two main tasks: normalization, segmentation.

Normalization of Cursive Script

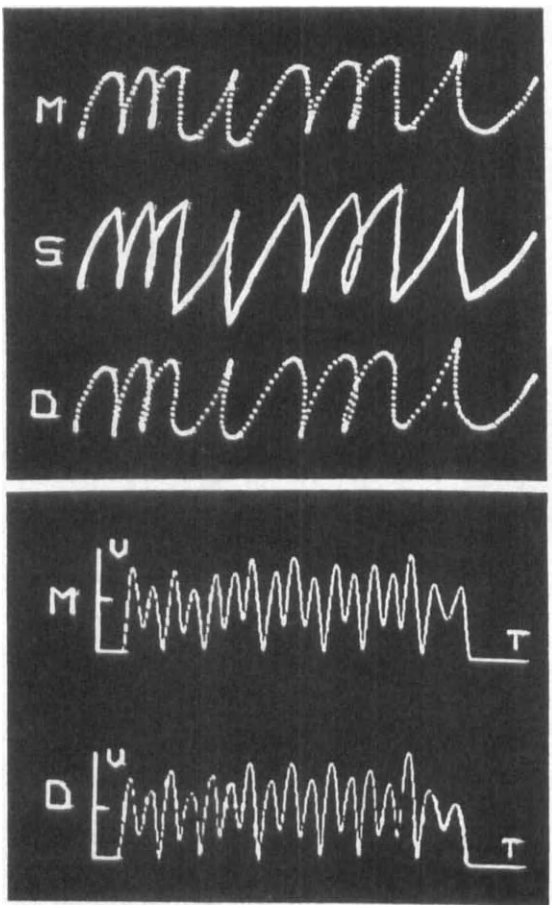
Four types of normalization can be distinguished: (i) time scaling, (ii) baseline compensation, (iii) slant compensation, (iv) size scaling.

The need of time scaling comes from the fact that different people have different writing speed and the same person can write with different speeds. What remains constant is the shape of the frequency spectrum of handwriting as a signal, which is characterized by a dominant peak around 5 Hz (Maarse and Teulings, 1984). Changing the writing speed displaces the peak frequency or, expressed differently, varies the overall number of strokes per second. Time normalization can then be defined as the problem of scaling the time axis (in practical terms, re-sampling the signals) in such a way that a standard writing speed is obtained, which can be measured either in terms of thepeak frequency or of the stroke rate. After time normalization has been performed, measures of durations, delays etc,. which are important in cursive script processing, become relative (i.e., more general) and the specification of the particular writing speed is stored in a single scaling factor.

The second type of normalization involves the baseline. The baseline may be defined as a smooth line which joins (or is close to) the bottom part of the strokes, except for some of them (e.g., the long strokes in "g, p, f" etc.). The notion of baseline involves a "selection" and this rules out the possibility of estimating it by low pass filtering the handwriting signals with a very low cutoff frequency (at least ten times smaller than the peak frequency), because filtering is a linear operator which does not select specific features. Nontheless, the curve which is obtained by low pass filtering is not far from the baseline (because the "exception strokes" are not statistically dominant) and it can be used at least to give a rough indication of right/left, and up/down. Once that is done, it is possible to carry out the selective process by (1) extracting the strokes as the handwriting segments limited by adjacent points of peak curvature (segmentation points), and (2) selecting the segmentation points where a down-going stroke is followed by an up-going stroke and at least one of them is a small stroke.

The third type of normalization involves the slant. As in the case of the baseline, two problems need to be solved: (i) slant estimation, and (ii) slant compensation. Slant may be defined as the average orientation of the handwritten trace at specific points. For example, we may select only the points of peak curvature or the points of peak velocity or, among them, only those which correspond to up-going or down-going strokes. In any case, after the selection criterion has been defined (the range of choices is caused by an arbitrary margin intrinsic in the notion of slant) and the average orientation at the selected points has been computed, slant compensation requires a "shear transformation" which makes the selected average orientation either zero or ninety degrees (depending on the selected criterion).

Figure 17 Fitting handwriting trajectories with circular strokes. D: experimental data. S: (circular) stroke representation. M: resulting trajectory of the model. Bottom Figure: velocity profile of the experimental data and of the model.



The fourth type of normalization involves size. This means two things: (i) one is the relative scaling between the horizontal and the vertical components of the script in such a way that some average shape criterion is met (e.g., normalized average "roundness," which is known to reliably classify male and female writers), and (ii) the other is the global scaling in order to obtain some standard size parameter (e.g., the average stroke length).

Segmentation of Cursive Script

After the normalization procedures have been applied to an individual cursive script, we can store individual global parameters (time, size, baseline, slant) and we can apply to the normalized trace the segmentation and coding concepts already discussed for trajectories in general.

In particular, we can use the same fitting procedure expressed by (19) which constructs the curved stroke representation (22). As already remarked, this kind of strokes are characterized by six parameters. However, it is worth noting that, at least for "regular" handwriting (Morasso and Mussa Ivaldi, 1982) it is possible to fit the data with circular strokes which have only three parameters (length, orientation, radius of curvature), as it is shown in Figure 17. In any case, the final result of the segmentation phase is a representation of the script as a chain of strokes characterized by shape descriptors. Such a script notation is the starting point for structural shape analysis. The future objective is to build allograph databases to be used in the automatic recognition of cursive script.

ACKNOWLEDGEMENTS

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FOOTNOTES

1. The rationale of the statement comes from the Taylor series expansion of a function in the neighborhood of a point.

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MODELIZATION OF HANDWRITING: A SYSTEM APPROACH

Réjean Plamondon
Francois Lamarche

INTRODUCTION

A few years ago, Vredenbregt and Koster (1971) designed a handwriting simulator based on two pairs of mechanically coupled D.C. motors. Each pair of motors was used for moving a stylus in two opposite directions along a specific axis of a cartesian coordinate system. The effect of motor coupling emulated the agonist-antagonist activities of the muscles involved in the writing process (Denier van der Gon and Thuring, 1965). Indeed, when a motor was actuated its partner operated as a generator, dissipating energy in a resistor and providing damping for the system, the required inertia being provided by the mass of the armature, stylus and other moving parts.

Voltage pulses of constant amplitude and variable duration supplied energy to the system. In accordance with results obtained from electromyographic recordings, these pulses would simulate the nervous stimuli responsible for the initiation of movements. With a set of motors having starting and stopping characteristics closely resembling those of skeletal muscles, the simulator was used to determine the timing of the actuations needed for the synthesis of specific handwritten symbols: Proper sequences of voltage pulses were found by trial and error, and natural looking letters were generated.

The quality of the characters produced by such a simulator has led us to a basic question: Since it is possible to simulate handwriting with pairs of D.C. electric motors, can we make use of the transfer function of this electromechanical system to: (1) extract, from the movement, an operational pattern of stimuli; (2) obtain a mean of segmentation and compression of the data and; (3) regenerate the original dynamics of handwriting using the extracted pattern of stimuli?

In this paper we propose the following scheme; first we derive the transfer function of the simulator, a third order system in the position domain.

Simplifications to this mathematical description are then presented and discussed through simple experiments based on the analysis of uniaxial handwritten movements. It appears that the approximate second order model is not suitable for perfect movement reconstruction. Detailed analysis of the experimental transient response of the system rather supports a third order model. However, the simplified approach is of practical interest for data compression since it allows for characterization of the system with only one parameter.

TRANSFER FUNCTION

Figure 1 shows a schematic of the system used by Vredenbregt and Koster (1971) to simulate handwriting. Only one degree of freedom (vg. one principal axis) is presented here. The movement of a stylus along this principal axis is generated by feeding the D.C. motors with a sequence of on-off voltage pulses. The speed of the stylus, v(S), can be linked to the voltage of an input stimulus, V(S), by a second order transfer function:

$$\frac{v(S)}{V(S)} = \frac{K_1K_2}{S^2(RF\tau_a\tau_m) + S(RF\tau_a + RF\tau_m) + (K_1{}^2 + RF)} \quad (1)$$

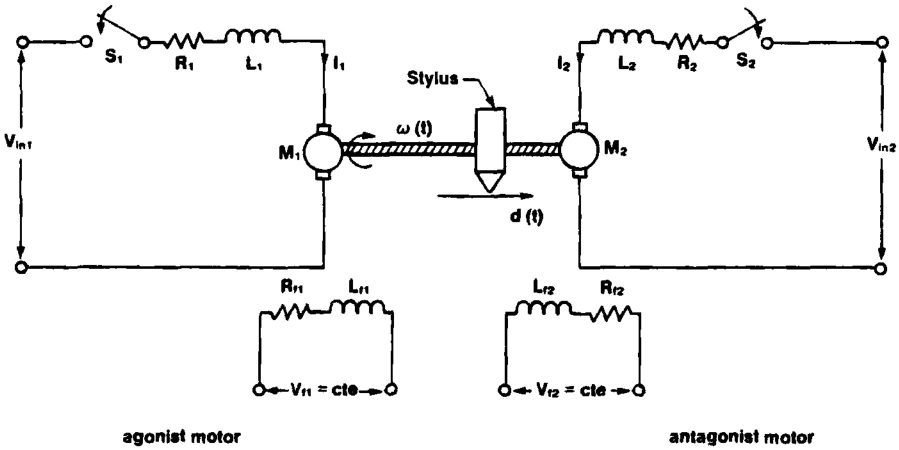
$$= \frac{G}{\left(\frac{S}{W_n}\right)^2 + 2\xi\left(\frac{S}{W_n}\right) + 1} \quad (2)$$

where:

L_1	=	$L_2 = L$
R_1	=	$R_2 = R$
τ_a	=	L/R
τ_m	=	J/F
J	=	moment of inertia
F	=	viscous friction coefficient
K_1	=	electrical torque constant
K_2	=	angular to linear speed conversion factor
ω_n	=	natural frequency
ξ	=	damping factor
G	=	gain

The normalized form of equation (2) clearly shows that we are faced with a second order system in the velocity domain. Two assumptions have to be stated prior to obtaining a description of the pentip speed as a function of time: First, the system has no tendency to oscillate when stimulated and therefore it is overdamped; second, in accordance with what is generally reported in the literature, it is assumed that the input stimuli V(t) consist of a rectangular pulse sequence. Consequently, the movement of the stylus

Figure 1 Electromechanical model.



along a principal axis could be interpreted as being a succession of step responses, the response to one particular step having the following form:

$$v(t) = G(1 + Ae^{-at} - Be^{-bt})U_{-1}(t) \qquad (3)$$

where

$$1/a,\ 1/b = |-\xi\omega_n \pm \omega_n \sqrt{\xi^2 - 1}|$$

$$A, B > 0$$

The initial condition provides another equation:

$$v(t)\Big|_{t=0} = G(1 + A - B) \qquad (4)$$

$$\text{In particular, if } v(t)\Big|_{t=0} = 0, \text{ then } B - A = 1 \qquad (5)$$

Since most of the studies dealing with handwriting analysis and simulation are concerned with position analysis, equation (3) must be integrated to obtain the step response of the system for the pentip displacement along one principal direction of movement:

$$d(t) = G\left[t - \frac{A}{a}e^{-at} + \frac{B}{b}e^{-bt} - \frac{B}{b} - \frac{A}{a}\right] U_{-1}(t) \qquad (6)$$

The model leads to a third order system in the position domain. It is one degree higher than the equations reported in previous studies on biomechanical analysis of handwriting (Denier Van der Gon, Thuring and Strakee, 1962; MacDonald, 1966; Yasuhara, 1975, Hollerbach, 1981; Dooijes, 1983) but this apparent discrepancy can be explained recalling that these studies were primarily concerned with a mathematical expression for the pen displacement as a function of the different forces involved in the process. If one assumes that the activation level of the muscles can be described as a first order response to the neural firing rate (Dooijes, 1984), an analysis of the pen displacement as a function of the neural stimulus would also result in a third order system for these previous studies. In fact, Yasuhara (1975) did work with a third order system since he fed a second order system with input stimulus having exponential or first order transition characteristics.

SECOND ORDER APPROXIMATION

Equation (6) is not easy to deal with, since five parameters must be known to simulate handwriting from a pattern of rectangular input stimuli. Moreover if one is interested more in data compression than perfect data reconstruction, this approach does not seem to be practical for a real-time analysis. A simple approximation is to work with a first order transfer function between v(s) and V(s):

$$\frac{v(S)}{V(S)} = \frac{G}{1 + \tau S} \qquad (7)$$

where

G = gain of the system

τ = time constant of the system

The response of the electromechanical system to a step input stimulus $U_{-1}(t)$ becomes:

$$v(t) = G(1 - e^{-\alpha t})U_{-1}(t) \qquad (8)$$

or

$$d(t) = \int v(t)dt = G\left[t + \frac{1}{\alpha}e^{-\alpha t} - \frac{1}{\alpha}\right]U_{-1}(t) \qquad (9)$$

where

$$\alpha = 1/\tau > 0$$

Equations (6) and (9) both have the same general form, that is:

$$d(t) = G\,[t + T_{TRn}(t) - C] \qquad (10)$$

where C is a constant

$T_{TRn}(t)$ is a linear combination of n exponential terms

$$T_{TRn}(t) = \sum_{K=1}^{n} P_K e^{-R_K t} \qquad (11)$$

G can be interpretad as being a gain proportional to the amplitude of the stimulation and $T_{TRn}(t)$ as being a characteristic of the system that translate the stimulation into a movement.

The approximation takes place when $T_{TR1}(t) = -\frac{1}{\alpha}e^{-\alpha t}$ is used instead of $T_{TR2}(t) = -\frac{A}{a}e^{-at} + \frac{B}{b}e^{-bt}$

Although this approximation has been questioned by Yasuhara (1975), it has been recently reintroduced by Dooijes (1984) on the basis of the small value of the time constant in the first order equation linking the driving force and the on-off input stimulus found on a modified version of a simulator described by Denier van der Gon, Thuring and Strackee (1962). In the context of the Vredenbregt-Koster simulator this assumption can be justified at first glance since in such a system the magnetic circuit of the D.C. motors is generally saturated (induced voltage actuation).

PRINCIPAL DIRECTIONS OF MOTION

A demonstration of any handwriting model validity is not as simple as it might seem since a complete proof would require the determination of the number and orientation of the principal directions of motion. Indeed, equation (6) depicts the behavior of an actuator along its principal axis and it is generally not meaningful physically to interpret the projections of that principal components on the orthogonal coordinate system of a graphic tablet, since the orientation of the principal axis with respect to the cartesian system is not known.

One simple but common view to solve the problem is to assume that the hand movement can be decomposed along two independent principal directions of an oblique coordinate system, one axis (X') resulting from a rotation of the hand about the wrist and the other axis (Y'), from the oscillation movement of the thumb, index finger and middle finger. As one can see from Figure 2, (where XY represent the orthogonal system of a digitizer and X'Y' stand for the two principal axis of the hand), any movement along one principal direction (A → B or C → D) will be directly observed as such if it is analysed globally in the XY coordinate system. For example, the wrist motion A → B will give:

$$v_X(t) \quad = \quad v_{X'}(t)\cos\theta_1 = G_{X'}(1 - e^{-\alpha t})\cos\theta_1 U_{-1}(t) \qquad (12)$$

$$v_Y(t) \quad = \quad v_{X'}(t)\sin\theta_1 = G_{X'}(1 - e^{-\alpha t})\sin\theta_1 U_{-1}(t) \qquad (13)$$

$$|v(t)| \quad = \quad \sqrt{v_X(t)^2 + v_Y(t)^2} = \sqrt{v_{X'}(t)^2\cos^2\theta_1 + v_{X'}(t)^2\sin^2\theta_1} \qquad (14)$$

$$= \quad |v_{X'}(t)|$$

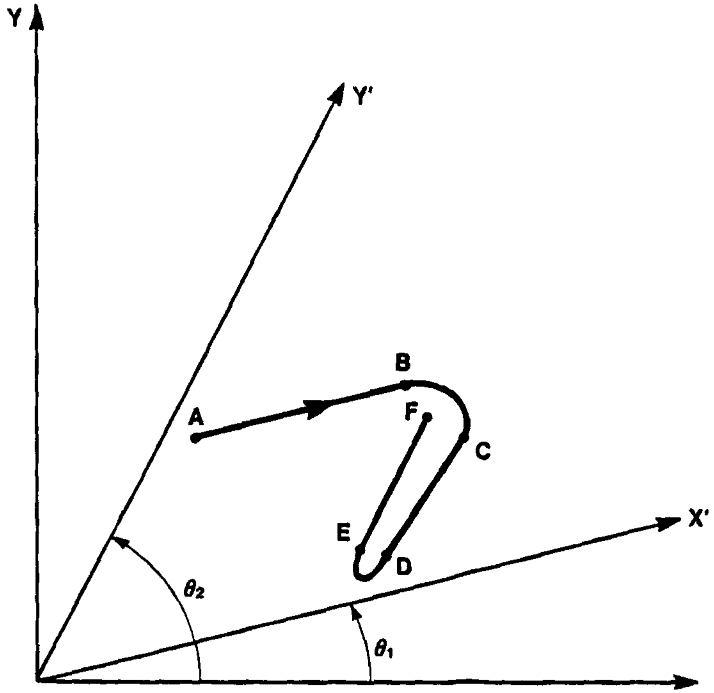
However, a similar analysis on any composite movement (that is any movement resulting from the action of both sets of actuators, as for segment B → C, D → E and E → F) will mask the individual contribution of each group of actuators, contribution which will not be easily discriminated unless θ_1 and θ_2 are known and do not vary with time (Dooijes 1983). In this general case we have:

$$v_X(t) \quad = \quad v_{X'}(t)\cos\theta_1 + v_{Y'}(t)\cos\theta_2 \qquad (15)$$

$$v_Y(t) \quad = \quad v_{X'}(t)\sin\theta_1 + v_{Y'}(t)\sin\theta_2 \qquad (16)$$

Two additional independent equations must be found to solve this four unknown problem. Otherwise, movements along X' and Y' axis cannot be analysed separately.

Figure 2 Prinicpal directions of motion.



MOVEMENTS ALONG ONE PRINCIPAL AXIS

In order to avoid this decomposition problem, simple experiments were conducted on movements generated along one single principal axis. Right handed subjects were asked to write single or repetitive linear segments by activating only their X' or Y' natural axis, that is, writing strokes segments from wrist rotation or finger oscillation movement respectively. The position of the pentip was measured with the help of a digitizer to which a special electronic module was connected. This set up recovers, among other things, the full analog pentip position, allowing the data acquisition system to work at higher sampling frequency, 500 Hz in most of these experiments (Maamari, Plamondon 1986). The data acquisition was performed in two steps (Plamondon 1984): the analog pentip position was first sampled via an A/D converter controlled by a microcomputer. This information was then transmitted to a host computer for off-line processing.

In these simple experiments, the forearm remains stationary and no slow left to right motion (trend component) had to be removed from the data. Prior to any analysis, the XY coordinates were converted into $C_d(i)$, the cumulative scalar displacement of the pentip along the movement axis:

$$C_d(i) = \sum_{i=1}^{n} |\Delta d_i(t)| \qquad (17)$$

where:

$$\Delta d_i = \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2} \tag{18}$$

The use of $C_d(i)$ is of practical interest here since it allows for a study of the global movement at once, irrespective of any XY coordinate system. This information is matched with the succession of step responses, obtained via summation of equation (10):

$$R_d(t) = \sum_{j=1}^{m} d_j(t - t_j) \tag{19}$$

where:

$$d_j(t - t_j) = \Delta(t_j)(G_j - G_{j-1}) \ [t + T_{TRnj}(t) - C_j] \tag{20}$$

Δ = translation operator

$\Delta(t_j)$ = time translation by t_j, t becomes $t - t_j$

with $\Delta(t_o)$ = 1
and G_o = 0, as initial conditions
j = stimulus number

The curve described by equation (19) is a succession of linear segments, linked together by exponential sections reflecting the steady state and the transient responses of the system respectively. A stroke, which is defined in this model as the movement resulting from a rectangular input pulse applied to one set of actuators, is thus composed of three successive sections (transient, steady state, transient). Each stroke can be described by referring to its two associated input stimuli and is easily specified using the following parameters: starting time (t_j), stopping time (t_{j+1}) and amplitude of the pulse, (G). If, in equation (20), $T_{TRi}(t)$ is used, only one time constant per transition has to be added in order to be able to regenerate the stroke.

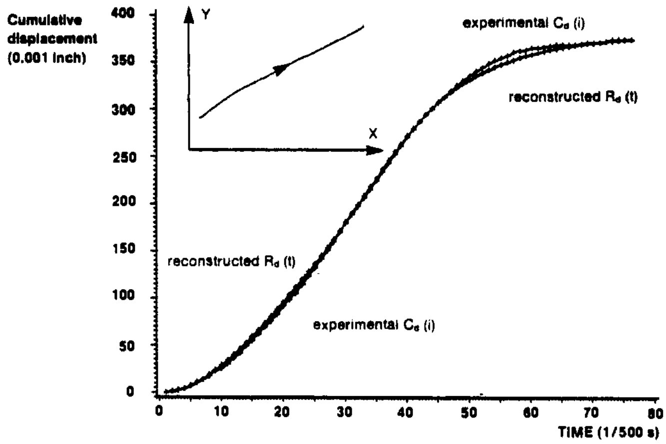
Extraction of input pulse features from $C_d(i)$ is performed by software based on the following algorithm (Lamarche, Plamondon 1984a):

1° evaluation of switching time taking place between transient and steady state responses using iterative computation of the speed for each experimental point i:
$v_i > v_{i-1}$: speed increases → beginning of a stimulus, $t = t_j$.
$v_i = v_{i-1}$: permanent response.
$v_i < v_{i-1}$: speed decreases → end of a stimulus, $t = t_{j+1}$.

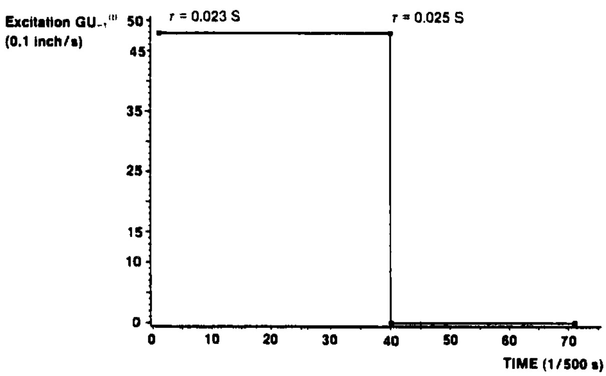
2° evaluation of the stimulus amplitude by computing the slope of the steady state portion of the cumulative scalar displacement curve $C_d(i)$. In forthcoming figures the stimulus amplitude represented by the product $GU_{i}(t)$, is expressed in inch per second.

The time constants τ_j used for dynamic curve synthesis are evaluated by a two-pass algorithm which starts movement reconstruction with an arbitrary value for τ_j and then makes appropriate corrections to each τj in order to

Figure 3 Analysis of a wrist movement (X'Axis).



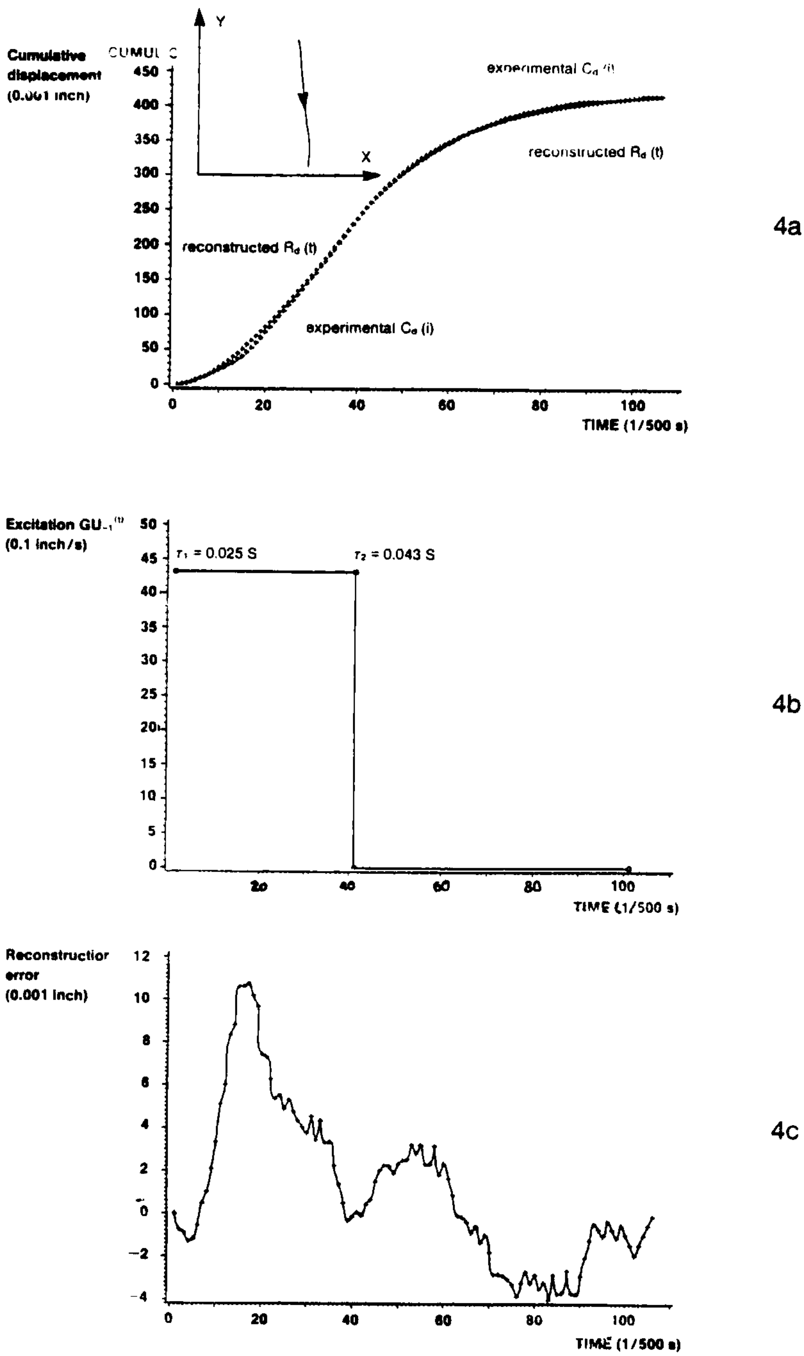
3a



3b

3c

Figure 4 Analysis of a finger movement (Y'Axis).



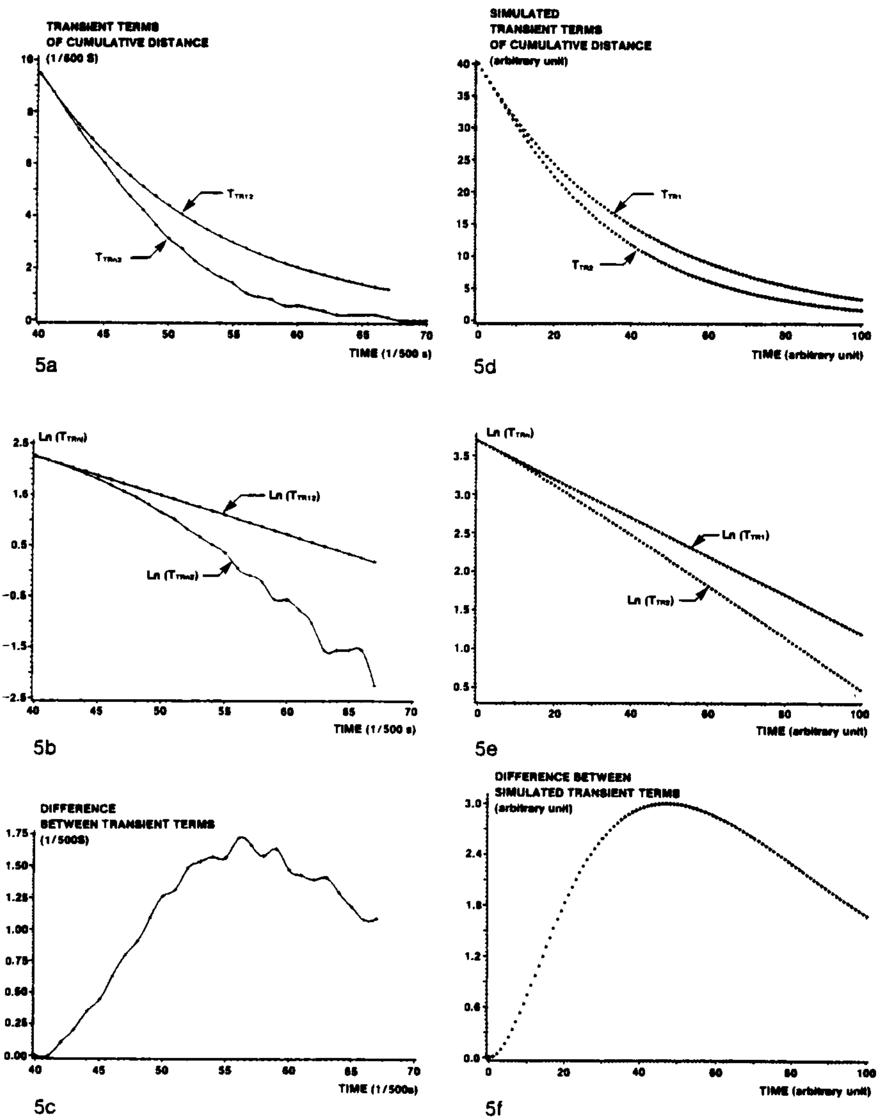
minimize errors in the steady state portions of the curve $C_d(i)$. The minimization of steady state errors is used as a synthesis criterion since it guarantees a minimum of discrepancies between experimental and synthetized data for portions of curve where the speed is maximum. Moreover it prevents error integration since the error is nullified prior to the beginning of any further excitation.

Figures 3 and 4 show typical results. Figure 3 reports on curves obtained from a single stroke intentionally produced by a rotation of the hand about the wrist (along X'). Curves of Figure 4 are obtained from a movement produced by the thumb, the index and the middle finger (along Y'). For each set of figures, the upper curve represents the cumulative scalar displacement of the pentip (experimental and synthetized) as a function of time for the specific movement shown in insert. The middle curve depicts the input pulse which has been extracted from the experimental data. The time constants used for movement reconstruction are indicated along the respective transition of the input stimuli. The lower curve plots the error between experimental and reconstructed cumulative scalar displacement curves. No filtering was applied to the experimental data, though the beginning and the end of each sample has been truncated in order to clean up the portion of signal under study.

As one can see from the lower graphs of Figures 3 and 4, using $T_{TR1}(t)$ in equation (20) and feeding it with the proper time constants and input pulses result in a movement synthesis with an accuracy better than $\pm$ 0.01 inch. The magnitude of the errors exceeds the random and bias error components encountered in the measurement of pentip movements with our system. Indeed, it has been shown for this particular set-up that the random error, mostly due to the digitizer jitter noise is within $\pm$ 0.002 inch (Maamari, Plamondon 1986). The systematic bias error results from the approximation of a continuous curve with a discontinuous series of straight lines. Since a sampling frequency of the special set-up used for data acquisition is high compared with the maximum speed of the pentip and since the sampled strokes were almost completely straight, the systematic error is certainly negligible here.

In this context, there must be a third component contributing to error curves of Figures 3c and 4c. Comparing these curves with the upper ones, $C_d(i)$ vs t, we see that the error is minimum in the steady state portion of the movement, positive for the transient response to an on-stimulus (increase of speed) and negative for the transient response to an off-stimulus (decrease of speed). This observation suggests that the biomechanical system does not behave exactly like a second order system. Indeed, it reacts more slowly to input stimuli than the theoretical simplified model, as would have been obtained if $T_{TR2}(t)$ had been used as a basis for reconstruction instead of $T_{TR1}(t)$.

Figure 5 Analysis of a transient response.



This latter inference can be indirectly confirmed if one isolates the transient portion of a cumulative scalar displacement by subtracting the anterior and actual steady state terms to the experimental data for the jth transient. Starting from tj, and assuming that the effect of the previous transient (occured at t_{j-1}) is finished, one obtains for the jth transient:

$$R_d(t) \approx \Delta(t_j)\,[G_j t + (G_j - G_{j-1})\,(T_{TRnj}(t) - C_j)] \qquad (21)$$

Subtracting the steady state term obtained from the experimental results and given by curve $C_d(i_j)$ for the same time interval, one can isolate the jth transient:

$$T_{TRnj}(t - t_j) = \frac{C_d(i_j) - G_j(t - t_j)(G_j - G_{j-1})\,C_j}{(G_j - G_{j-1})} \qquad (22)$$

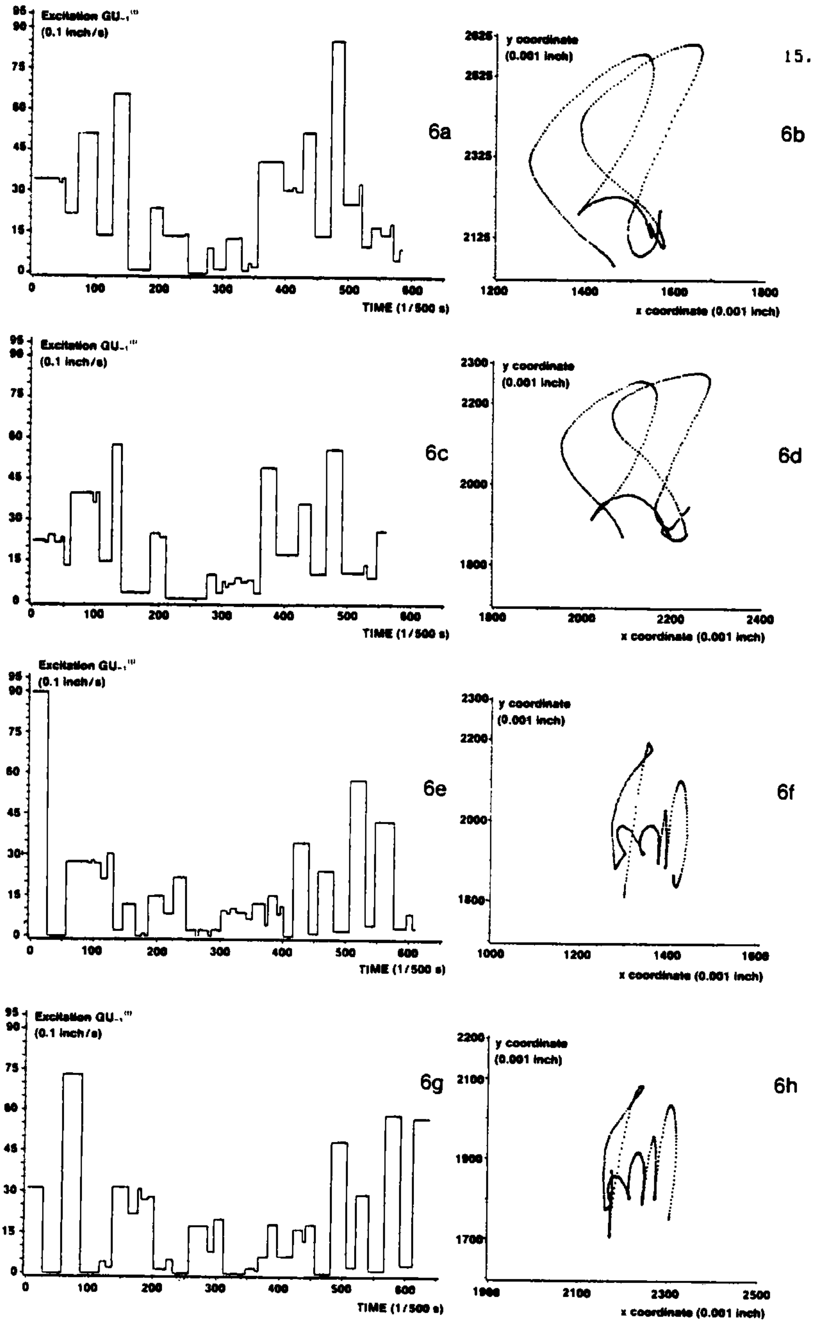
Figure 5a shows the value of T_{TRn2} (equation 22) computed from the second transient (j=2) of the experimental cumulative scalar displacement curve depicted in Figure 3a. Figure 5b reproduces the same curve on a semilogarithmic scale. In both figures, a curve corresponding to T_{TR12} has also been plotted. Indeed, for a reconstruction based on the use of T_{TR1} and on minimization of steady state errors between equations (6) and (9), it can be shown that both T_{TR1} and T_{TR2} exhibit the same initial conditions. The slope (e.g., the reciprocal of the time constant) used for T_{TR12} in Figure 5a corresponds to the slope of the very first points of the experimental curve of Figure 5b. Because the computational process is not exempt of errors, the time constant obtained here (0.029 s) does not correspond exactly to the time constant used for reconstruction in Figure 3c (0.025 s). However it constitutes a very good first approximation.

Figure 5c shows departures between transient terms T_{TRn2} and T_{TR12}. As one can see from this latter curve, the behavior of the biomechanical system is not perfectly well modeled by T_{TR12}. In Figures 5d, e and f, computer simulations have been used to generate curves corresponding to terms T_{TR1} and T_{TR2}. The similarities between pairs of curves (5a and d, 5b and e, 5c and f) strongly suggest that the biomechanical system behaves like a third order system and would be better described with the help of equations 2 or 6, provided there exist some ways for parameter evaluation.

DATA COMPRESSION APPLICATION

To our experience, the use of a single axis second order approximation for handwriting synthesis has only been successfull for the reconstruction of very simple specific movements. Some attempts to reconstruct more complex movement with this simplified model (e.g., movements involving more than one set of actuators) has resulted in a tenfold factor increase for the dynamic reconstruction error. Although such error levels have not been judged acceptable in a lot of synthesis experiments (Yasuhara, 1975), the approximate model may offer an advantage for data compression in experiments were perfect signal reconstruction is not the major objective, since only one time constant is necessary to characterize a transient response in this case. Also,

Figure 6 Stimuli exraction from initials.



it should be emphasized that curve segmentation, which is based on switching points extracted from curve $C_d(i)$, is independent of n, the order selected for T_{TRn}.

An analysis on data compression and segmentation has been recently reported (Lamarche and Plamondon, 1984b) for experiments dealing with handwritten signature. The model has been directly used for signal analysis under the assumption that there was always one axis along which forces were predominant at a given time, the orientation of this axis being irrelevant. More than 2,400 initials have been acquired from 39 subjects participating to the experiments. For each sample cumulative scalar displacement curves were first computed and their input stimuli were extracted using the same algorithm mentioned earlier (Lamarche, Plamondon 1984a). By doing so, each effective stroke was associated with two input steps and described by its starting time, duration and amplitude, instead of all the coordinates of the pentip displacement. Data compression ratio of up to 50:1 have been obtained in these experiments (on a 500 Hz sampling rate basis).

Figure 6 shows two pairs of such input patterns. The corresponding initials are displayed on the right hand side of each graph. No normalization was performed on these data. As one can see, there is roughly a 4/3 factor between the mean amplitude of the stimuli for the first pattern (Figure a) with respect to the second (Figure c). This correspond to the 4/3 ratio between the first (Figure b) and second (Figure d) specimen. Both signatures were however executed in almost the same time length. These facts are in accordance with results published by Denier van der Gon and Thuring (1965) and Yasuhara (1975). Moreover, comparison of initials of similar dimensions (Figures f and h) confirm the conclusion about the non constant amplitude of the input stimuli over an entire sample, recently published by Dooijes (1983) for a similar model (Figures e and g). Except for slight misalignment in the time axis due to non reproductible hesitation at the beginning and the end of a signature, the graphical similarities are reflected in input pattern curves for initials of a same subject (a vs c, e vs g). Dissimilarities between initials from different subjects are also still apparent (a or c vs e or g) through the dynamic transformation. Whether enough information is kept in the segmentation/compression process is beyond the scope of this paper, since a lot of studies will have to be performed on signal correlation prior to any conclusion on this point.

CONCLUSION

The limitations on the use of a simplified second order model to study handwriting become evident if the position data can be sampled at higher rate than the common 60 to 100 Hz generally available on commercial digitizers. In this latter case, third order effects in the transient response of the system are not perceptible because of a lack of data (Lamarche 1985). Derivation of equation (8) to obtain an expression for the acceleration according to the simplified model does not lead to a continuous function of time. Therefore, the shape obtained for experimental acceleration signals (Brault 1983) could not be matched with prediction of this simplified model. This argument together with reconstruction experiments and study of transient portions of experimental curves provide evidence that the exact transfer function between the input program of on-off stimuli and the pentip displacement is at least a third order system. However, a perfect reconstruction of handwriting is far from being garanteed if one uses such a function in a practical environment. Indeed, handwriting synthesis would require at least two equations similar to equation (6) with five unknown parameters per equation together with a matrix equation for coordinate transformation from the XY plan of the digitizer to the principal direction of movement (equations 15 and 16), introducing another set of two unknown factors. In this perspective, a second order system might constitute a good compromise for approximating the writing movements.

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AN ADAPTIVE SYSTEM FOR HANDWRITING RECOGNITION

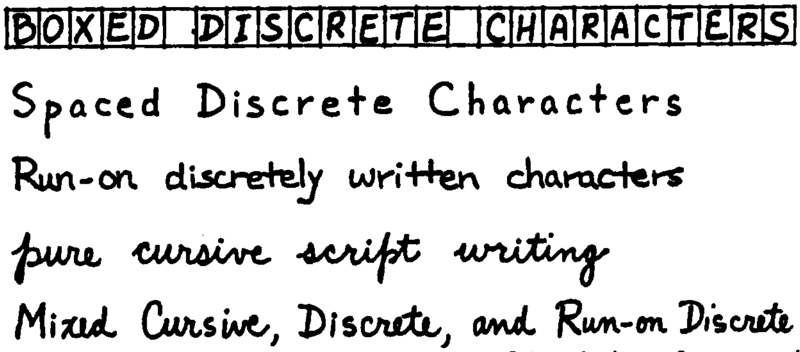
C. C. Tappert

INTRODUCTION

In recent years there have been significant advances in the design of handwriting workstations. High-quality, thin, transparent tablets overlaying flat displays may soon be available and economical. This combination provides the user with a hand-held writing stylus and "electronic ink." That is, a trace of the motion of the stylus tip as it is captured by the machine is displayed directly under the stylus. This capability is analogous to working with pen and paper in two respects: the writing area and display are essentially the same surface, and the displayed trace of the stylus gives the user immediate feedback of the writing captured. This immediate feedback is important for the reliability of this mode of communicating with machines. There have been advances in software, particularly in recognition algorithms and interface design, as well as in hardware which enables computationally-intensive algorithms to be implemented at workstations. Along with these advances there has been a growing interest in communicating with machines in a person's natural modalities, such as speech and handwriting.

For handwriting on a tablet terminal the range of types of writing for English and most European languages is illustrated in Figure 1. These are listed in order of increasing difficulty of machine recognition and can be classified in terms of the level of letter segmentation required. Discrete letters written in boxes are segmented by the writer when entering each letter in a box, and a machine procedure for letter segmentation is not necessary. Spaced discrete letters require a machine procedure for spatial letter segmentation. Such a procedure is referred to as an "external" segmenter since it can be apart from or external to the recognizer. The remaining problems require more advanced segmentation techniques. This type of segmentation is referred to as "internal" segmentation since it generally requires the interaction of letter segmentation and recognition. The run-on discrete case is somewhat easier than those involving cursive writing since, by definition, each letter consists of one or more strokes and segmentation points can only occur at stroke ends. A stroke consists of the writing from pen down to pen up. For the cases involving cursive writing, segmentation within strokes is necessary since several letters can be made with one stroke.

Figure 1 Handwriting types.



Currently it appears that the most successful technique for recognizing segmented discrete characters is that of elastic matching, also referred to as dynamic time-warping. Most of the papers cited here describe recognizers which use elastic matching. For example, elastic matching has been used for recognizing Chinese characters, e.g., (Ikeda, et al., 1978; Sakai, et al., 1984; Wakahara, et al., 1983; Wakahara, et al., 1984 and Yoshida, et al., 1982) and discrete Latin letters, e.g., (Burr, 1983; Tappert, et al., 1983 and Tappert, 1984). This technique has also been extended to the special case of pure cursive English writing (Tappert, 1982). What has been needed, at least for Latin alphabets, is a unified approach for handling the various types of writing illustrated in Figure 1. In this paper a new recognizer is described which handles all of these kinds of writing in a unified manner. Additionally, on pure cursive writing this method is both faster and more accurate than that previously described (Tappert, 1982).

ALGORITHMIC PROCEDURES

Prototypes are used to provide references against which unknown characters are matched, with each alphabet character being represented by one or more prototypes. The system has three modes of operation — training, updating, and recognition. In the training and updating modes, characters are written according to a specified text and additions are made to the set of prototypes. In the training mode all the written characters are used to make prototypes, whereas in the updating mode only characters which meet certain criteria, such as not being recognized correctly, become prototypes. In the recognition mode, the prototypes are used to recognize unknown words of writing.

The recognition system uses two procedures. The external segmentation procedure separates words from one another in all writing except spaced discrete characters where it separates characters from one another.

The recognition procedure then operates on one word at a time. Within the processing of a word the character segmentation and recognition steps are combined into an overall scheme. Basically, this is accomplished in three steps. First, potential or trial character segmentation points are derived. This is done in a manner which ensures that at least all true segmentation points are found, although extra ones may also be selected. Second, all combinations of the segments that could reasonably be a character are sent to the character recognizer. The character recognizer matches a candidate character against each prototype and returns ranked character choices and corresponding matching distance scores (Tappert, 1984). Finally, the character recognition results are sorted and combined so that the character sequences having the best cumulative distance scores are obtained as the best word choices. For a particular word choice the corresponding character segmentation is simply the segment combinations that resulted in the chosen characters.

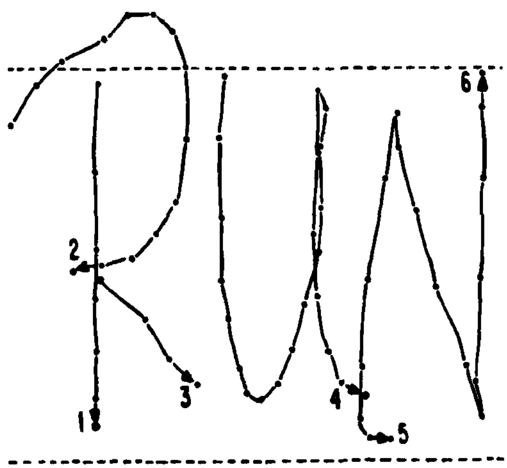
These steps are now described in more detail for run-on discrete writing. A hand printed character consists of one or more strokes. Since each character terminates at a stroke end, then, by considering all stroke ends as possible character segmentation points, no character segmentation point is missed, although there are extra ones for characters consisting of more than one stroke. Since some characters consist of several strokes, various stroke sequences must be sent to the character recognizer. The procedure allows for stroke sequences of up to a specified number of strokes, N, to be sent to the character recognizer. Normally, N is set to the maximum number of strokes possible in the alphabet employed, e.g., four for English. Thus, at each potential segmentation point, the stroke preceding the segmentation point, the two strokes preceding the segmentation point, etc., up to the N strokes preceding the segmentation point, are sent to the character recognizer. The procedure then sorts the candidate characters and corresponding distance scores. This is an exhaustive process where all combinations of strokes are tried, with the constraint that each stroke is used only once. The sequences of candidate characters yielding the best cumulative distance scores are presented as the best word candidates.

Figure 2 Example of run-on hand printing.

An example of the processing performed by the recognition procedure will be described. A sample of run-on discrete writing is shown in Figure 2. Figure 3 shows the machine representation of the word RUN of that sample. The word consists of six strokes. The information obtained in the machine processing of this word is shown in Figure 4. After each stroke is received, the machine presents recognition choices of that stroke as well as those of the other sequences of strokes ending in that stroke (corresponding matching distance scores are in parentheses). For example, after stroke 6, the single stroke 6 is recognized as a V with v as second choice, and the stroke sequence

5+6 is recognized as N. This information is then followed by the current best choices of character strings (corresponding cumulative distance scores are in parentheses). For example, after stroke 6, the best choices of character strings, which in this case (final stroke of word) are also the best word choices, are RUN, RULV, and RULv. The correct recognition choices and the correct word choice are circled; note that the cumulative distance score is the sum of the corresponding matching distance scores. The information presented in Figure 4 has been abbreviated for the sake of clarity, i.e., N is three, the number of character recognition choices is two, and the number of character string choices is three. Also, Figure 4 presents only those choices whose distance scores, when normalized by the number of sample points, is within a threshold. In this example the alphabet was limited to the upper and lower case letters.

Figure 3 Machine representation of RUN showing stroke sequence.



This technique readily extends to cursive writing. Recall that a stroke has been defined here as the writing from pen down to pen up. Thus, for example, the word and written cursively is generally made with a single stroke. Therefore, the only addition required is a preliminary segmentation procedure that yields potential character segmentations within strokes. This segmentation procedure should be designed so that true character segmentation points are rarely missed and that extra segmentation points are kept to a minimum. Potential segmentation points are found where ligatures can occur within strokes. For English high ligatures follow b, o, v, and w, and low ligatures follow all other letters. High ligatures are located near the midline, i.e., at the height of most lower case letters, and low ligatures are located near the base line. At these ligatures the pen tip is moving in essentially a left to right direction. Once these potential segmentation points are found, the resulting stroke segments are then processed in the same manner as are strokes of hand printing.

Figure 4 Recognition output for the word RUN.

After stroke 1	stroke 1		
1st choice:	L (90)		
2nd choice:	I (142)		
Best char strings:	L (90)	I (142)	
After stroke 2	stroke 2	strokes 1+2	
1st choice:	P (298)	P (170)	
2nd choice:		D (246)	
Best char strings:	P (170)	D (246)	LP (388)
After stroke 3	stroke 3	strokes 2+3	strokes 1+2+3
1st choice:		R (294)	R (222)
2nd choice:			B (346)
Best char strings:	R (222)	B (346)	LR (384)
After stroke 4	stroke 4	strokes 3+4	strokes 2+3+4
1st choice:	U (123)		
2nd choice:	u (235)		
Best char strings:	RU (345)	Ru (457)	BU (469)
After stroke 5	stroke 5	strokes 4+5	strokes 3+4+5
1st choice:	L (69)	U (297)	
2nd choice:	c (142)		
Best char strings:	RUL (414)	RUc (487)	RU (519)
After stroke 6	stroke 6	strokes 5+6	strokes 4+5+6
1st choice:	V (89)	N (147)	
2nd choice:	v (150)		
Best char strings:	RUN (492)	RULV (503)	RULv (564)

EXPERIMENTAL RESULTS

Results for discrete and cursive writing were previously described (Tappert, et al., 1978; Tappert, 1982 and Tappert, 1984). The results presented here are for a small sample of run-on discrete writing from one writer. They are of a preliminary nature and were obtained to test the operation of the new unified recognition system. Although based on a small sample of writing the results exhibit the general types of error also found in the previous studies involving larger writing samples (Tappert, 1982 and Tappert, 1984). Therefore, these results will be used as the framework in which to discuss the general types of error which have been found to occur using an elastic matching recognizer for the recognition of Latin characters. The recognition system, implemented in Pascal, runs on the IBM System/370 and the IBM PC/AT.

The alphabet consisted of the 26 upper and 26 lower case English letters and the 10 digits. Writing samples were taken from a single writer who was not familiar with the system. The handwriting samples were written on 1/4 inch lined paper which was aligned on an electronic tablet. Coordinate data obtained from the tablet have a resolution of 0.005 inch and were sampled at 80 samples/second.

The writer was asked to write three specified texts. The first was written as spaced discrete — that is, the writer was asked to leave space between the characters. These data were then used to create the initial prototype set. The second and third were written as run-on discrete — the writer was asked to leave space between words but was permitted to write the characters within a word so that they touched and even overlapped. Data from the second text were used to update the prototype set with additional prototypes taken from run-on writing. The first two texts each contained at least three occurrences of each character of the alphabet. The third text was used for obtaining data to measure the accuracy of the system. This text consisted of 72 words containing 325 characters with good distribution among the upper and lower case letters and the digits. Recognition was performed using the prototypes obtained from the writer as indicated.

Our main interest was in measuring shape recognition accuracy, which was 98.4 percent. "Shape" here refers not only to the final visible shape of a character after it is written, but also to the temporal production properties of the character, such as stroke order and direction, which are important in the elastic matching process. A total of 5 errors were due to inaccuracies in the recognition process. These include h recognized as n, y as g, and U as O. In general, errors of this type occur when an input letter is similar to a different alphabet letter, or a combination of letters similar to another combination of letters, such as cl versus d.

The raw character recognition accuracy, 85.8 percent (279/325), was also of interest, but does not reflect the accuracy of shape recognition. Three types of error occurred which must be handled by strategies external to the shape recognition process. The first type, accounting for 25 errors, occurs when different characters are not distinguishable out of context. For example, the characters 0 and O were written essentially identically, as were l, 1, and I, and are clearly not distinguishable by human or machine. Other errors of this type were between some of the similarly written upper and lower case letters C, c; K, k; O, o; P, p; S, s; V, v; W, w; X, x; Y, y; and Z, z. The second error type, accounting for 14 errors, is referred to as new variation, where a character is made differently, e.g., in terms of stroke order or direction, than any of its prototypes. For example, although the writer's usual stroke order for T was the vertical stroke followed by the horizontal crossing stroke, the reverse stroke order was occasionally used and resulted in error. The third type, accounting for 2 errors, is referred to as constraint deviation, where the writer does not maintain compliance with instructions. Here, the errors occurred because the letters were not written discretely, but were connected, as in cursive writing. For example, in writing the word to this writer used the same stroke to cross the t and write the o.

The first type of non-shape error, those due to the writer not making the characters distinguishable, can be greatly reduced, if not eliminated, in several ways. First, the writer can be taught to make the characters distinguishable. Second, depending on the application, the subset of the alphabet to which a character belongs, uppercase, lowercase, or digit, can be determined either precisely by the application or with some degree of accuracy by algorithms which rely on context. This is referred to as "alphabet selection." For example, a spreadsheet application would usually expect only digits. (A spreadsheet is an electronic representation of a ledger sheet, divided into columns and rows.) An address form application might require upper case and digits. Text within a paragraph would normally be lower case, with upper case for proper names, the beginnings of cy goes to 93.5 percent (304/325).

The second type of non-shape error, new variation, diminishes over time as more prototypes are added and the system is trained to the full range of the writer's variation. The third type of error, constraint deviation, may also diminish as the writer adapts to the constrained writing environment provided by the system. Discounting these types of error as not being due to shape recognition, accuracy goes to 98.4 percent (304/309). This represents the accuracy of the shape recognition process.

DISCUSSION

Chinese Versus English Writing

For purposes of the discussions to follow, it is desirable to compare Chinese and English (Latin alphabet) writing with respect to their properties and the recognition strategies which have been applied to them. There are many characters: a basic vocabulary consists of perhaps 3000 characters, and a character has an average of about 10 strokes. For English, while a comparable word dictionary is generally larger than that for Chinese, the set of basic writing units (alphabet) is much smaller. English words consist of sequences of letters, about 5 per word on the average. The alphabet has 26 letters and, in contrast to Chinese characters, each letter has two forms, upper and lower case. Letters consist of few strokes since there are only a small number of them to be distinguished. Uppercase hand printed letters consist of about two strokes per letter on the average, lowercase about one stroke, and cursive writing less than a stroke per letter. In order to differentiate between upper and lower case letters it is necessary to know the line spacing, e.g., S versus s, and the position of the letter relative to the baseline, e.g., P versus p.

Handwritten Chinese characters are generally separated spatially, one from the other; in fact, they are often written in boxes. Handwritten English words are generally written on lined paper and separated spatially. However, letters within a word are not generally separated spatially. Several cursively written letters are often written with a single stroke, and printed letters often touch or overlap even though written with different strokes.

Character or letter formation for both Chinese and English manifests variation in stroke number and stroke order. English may have more variation in stroke direction than Chinese. The same appears true for retraces. A retrace is the overwriting of a stroke, generally done to avoid a pen lift, e.g., the single stroke R described below.

The differences described above are reflected in two particular recognition strategies. For Chinese the basic the recognition strategy employed, cf. (Ikeda, et al., 1978 and Yoshida, et al., 1982), recognizes Chinese characters through the use of a generalized prototype set for all writers consisting of one prototype for each character. For English the recognition strategy described herein operates on word units, which are not the units that correspond to prototypes. Thus, an additional strategy is required to divide the word into pieces, recognize the pieces, and reconstruct the word. The character prototype sets are individualized to the writer and a character can have several prototypes in order to handle intra-writer character variation.

Speed, Accuracy, Flexibility

Ideally, a handwriting recognizer can be designed for maximum speed, accuracy, and flexibility. However, when used in a workstation, a handwriting recognizer may have to be designed to compromise among these properties. The recognition algorithms must be fast enough to be usable when implemented on a microprocessor. Typically, this means that they must operate at writing speed: about 2 characters per second for discrete or 3 characters per second for cursive writing. In addition, the recognizer must be accurate enough to be acceptable by the user and, finally, the recognizer must be flexible, that is, it must handle a reasonably wide range of handwriting input.

Depending on computing power, the characteristics of speed, accuracy, and flexibility may be in conflict. For example, high accuracy is attainable if the writing is highly constrained, e.g., each character written in a box, and produced carefully. Also, fast recognition can be attained at the expense of reduced accuracy. For example, since matching time is proportional to the square of the number of points per character, reducing the number of points per character greatly reduces the matching time. However, accuracy also decreases as the number of points per character is decreased (Kim, et al., 1984).

In terms of accuracy, the present system using the elastic matching procedure does well when different alphabet characters are made differently and consistently. If context is not available, the writer must be aware that different characters are to be made differently. The writer can learn this by direct instruction or through interaction with a real-time system. Similarly, the writer can learn to write characters consistently or to add additional prototypes to handle the variation.

Classification of errors is important because through precise error classification proper attention can be given toward improving the recognition system. The first error type, different characters not distinguishable from each other, can be viewed in a number of ways. If the writer was told to make the characters distinguishable, one from another, then these errors are really type three, constraint deviation. If not, they can often be handled by alphabet selection. In either case, they cannot be attributed to the shape recognition process. The second type, new variation, is somewhat similar. If the writer was told to make each character consistently, then these errors are constraint deviation. If not, they can be handled by additional prototypes and, again, cannot be attributed to a shape recognizer. However, if the recognizer is designed to handle some variation, such as variation in stroke number and order, e.g., (Wakahara, et al., 1983), then the errors can, indeed, be attributed to the recognizer. The third type, constraint deviation, is attributable either to the writer or to the lack of flexibility of the recognizer.

On closer examination of the errors attributed to the shape recognition process, it appears that many of these errors could be eliminated with improved or additional preprocessing, such as slant and baseline drift correction. Because writing which wanders from the baseline can be viewed as a "drift" of the effective baseline, this phenomenon is called baseline drift. Postprocessing could also be used to distinguish between similar characters such as h and n, cf. (Sakai, et al., 1984). Thus, it appears that shape recognition accuracy can be further improved.

We now turn to flexibility. Writing on a tablet with no constraints can be as varied as writing with pen and paper. At the other extreme, the writing can be limited to characters printed carefully, one to a box, and each character further limited to a specific number, order, and direction of strokes. Generally speaking, flexibility is concerned with where the characters or words are written, such as on lined paper or spaced one from another, and how they are written, such as with variable number of strokes, etc.

Flexibility with regard to number, order, and direction of strokes is interesting in its own right. In most of the early work on the recognition of Chinese characters, the writing of each character was restricted to a specific number, order, and direction of strokes, e.g., (Ikeda, et al., 1978 and Yoshida, et al., 1982). More recently, algorithms for Chinese character recognition have been developed to reduce writer constraints with regard to stroke number and order. A simple approach for handling the differences in stroke number alone is to connect all strokes into a single stroke (Yoshida, et al., 1982). A more sophisticated approach handles both stroke number and order variation (Wakahara, et al., 1983 and Wakahara, et al., 1984). This is accomplished by matching each stroke of the unknown against each stroke of the prototype, finding the best stroke correspondence, and, when the stroke numbers differ, using linkage ruus to combine strokes appropriately. This permits retention of the fixed set of prototypes, one for each character.

For the Latin alphabet, our approach, cf. (Tappert, et al., 1978; Tappert, 1982 and Tappert, 1984) has been to have each writer establish his own prototype set. All intra-writer variation is handled by the system simply by adding prototypes, which serves to increase flexibility; yet this variation is limited by restricting it to a single writer. English has a relatively small number of characters and also few strokes per character. Thus, this approach is feasible for English but probably not for Chinese. Significant intra-writer variation, such as differing stroke order or direction, is handled simply by storing additional prototypes. While this approach is flexible in that the writer is not constrained in his character production, the writer must take time to create prototypes. In fact, the more variation a writer has, the longer the time required to attain a prototype set which adequately represents his writing. This is why it is important to make the adding of prototypes easy in an interactive system (see below).

Differences in stroke number alone are handled in a manner similar to connecting all strokes into one. An example of this follows. A three stroke R can consist of a vertical stroke from top to bottom, a curved stroke which together with the first makes a P, and a straight stroke going from the end of the curved stroke down to the right (cf., Figure 3). A common two stroke variation of this R results when the latter two strokes of the three stroke R are made in one stroke. For these two R's the parameter representations used for matching are essentially identical. This is true for any variation in which a stroke continues from where the preceding stroke left off, i.e., a variation which differs only in an extra pen lift. A single stroke variation of the two stroke R can also be produced by connecting the two strokes, though, in this case, such a connection involves a retrace of the original first stroke. Due to the additional writing required for the retrace, this one stroke R has a different parameter representation.

With flexibility in mind we return to the earlier mentioned problem that different characters are often made indistinguishably. From context, one generally has no problem distinguishing 0 from O even when they are written identically. Therefore, the approach giving greater flexibility is to incorporate the intelligence necessary to make the required distinctions. For many applications, it may be possible to reduce the choices appropriately with modest effort. Thus, for many spreadsheet applications the alphabet is simply restricted to the digits. Strategies for more complex situations would include use of dictionary lookup and statistical information. Statistics could be used, for example, to indicate that a digit is unlikely in a word consisting mostly of letters and that an uppercase letter is unlikely in a word of lowercase letters except at the beginning of the word. However, for the completely unconstrained case, the intelligence required would be substantial.

Finally, reasonable speed of computation can be achieved with work in one or more of three areas. First, the repeated use of elastic matching can be limited by pruning, that is, by using alternate, fast characterization or classification methods which, although not highly accurate, can safely reduce the number of prototypes to be matched. Second, methods can be devised for cutting short the elastic matching computation for unpromising choices, e.g., (Sakai, et al., 1984). And third, the computation time for the elastic matching itself can be reduced, for example, by using an attached, special-purpose microprocessor or a custom chip similar to the dynamic-time-warping chips used in speech recognition.

Pruning is a particularly interesting areas. A highly efficient pruning method, used in most of the early Chinese character recognizers, is to match only characters with the same number of strokes. This is particularly effective for Chinese because of the wide distribution of stroke numbers among the characters. On the other hand, because of the large average number of strokes for Chinese characters, relative to English, more variation in stroke number is to be expected. This can be handled either by writer constraint, as in the early Chinese character recognizers, by an increase in prototype storage and establishment time as is done for English, or by more advanced algorithms as in the recent Chinese character recognizers. Pruning can also be based on other measures, such as the number of points per character or whether the strokes of a character are curved or straight.

Interactive Systems

The recognition system described here is to be used in a real-time interactive environment. Some of the requirements and problems of doing this are discussed. The range and sequence of possible actions by a writer during handwriting can be complex. On the one hand, a writer is only constrained by what he can do with paper and pencil. On the other hand, machine recognition of handwriting is still in its early stages of development and cannot handle handwriting input in its most unconstrained form. For example, at this time it would be difficult to recognize writing without baselines or writing with severe baseline drift, severe size changes, or severe variation in writing slant by the same writer.

The present recognition system has two components, a word segmenter and a word recognizer. It is necessary to bridge the gap between the writer and these recognition components. This bridging is performed by an application user interface which constrains the writer's actions to manageable proportions, controls the handling of the writer's strokes, structures the information sent to the recognition components, and presents the recognition results to the writer.

Some of the problems encountered in the design of the application user interface are now described. In order to provide a fast response, suppose that each new stroke obtained from the tablet is first directed by the user interface to the segmenter, that any new or revised words are immediately sent to the recognizer, and that the recognition result is displayed at the completion of each word. By way of illustration, consider the writing of the character H and its stroke by stroke processing. Assume a three stroke H consisting of the left vertical stroke, the right vertical stroke, and the connecting horizontal stroke. The first stroke would likely be recognized as l, and the second, being spatially separate, would be considered the start of a new word by the segmenter. The start of a new word signals that the previous one is complete causing its recognition result to be displayed. Finally, the connecting stroke would cause the segmenter to collapse these words, which, together with the connecting stroke, would be recognized as H. The user interface, having already displayed l, would then have to replace that with H. Thus, the processing of strokes as soon as they arrive, driven by the real-time requirement, can cause premature segmentation and, thus, incorrect recognition, resulting in the subsequent need for revision.

The desired user interface will place the writer in a tight feedback loop when performing prototype establishment and error correction. This is necessitated by the adaptive nature of the recognition system. A scenario to add prototypes from run-on or cursive writing might be as follows. The display could initially contain several lines of prompting text, each followed by a reasonably sized, lined writing area into which the user writes the text. At the top of the display there may be instructions describing any constraints imposed on the writer. Then, as the user completes, say, a line of writing, the internally segmented letters are displayed together with their names. This segmentation is examined and, if accurate, prototypes are created from the character data; if not accurate, another sample of the writing is taken.

A scenario for error investigation and dynamic prototype creation and deletion, which can occur upon misrecognition of a word, might be as follows. The writer notices that one of the words he had written is not recognized correctly. If the original handwriting is no longer displayed, he requests that it be displayed. He then requests that the display be augmented by the recognition results for the word in error. Such a display would include plots of the segmented letters in the original writing of the word and corresponding plots of the prototypes yielding this choice. The writer then decides that one of the letters should not have been misrecognized. He then requests a display of all prototypes of the letter which was incorrectly recognized. He deletes one of them from the prototype set. Furthermore, he decides to add the letter which was not recognized correctly as an additional prototype of that letter. He then requests that the word be rerecognized using the revised prototype set to verify that the word can then be correctly recognized. Finally, he requests elimination of all augmentations to the display concerned with error correction and prototype investigation, and continues writing new material. All of these requests are made by touching tablet menu points and, if necessary, a "from" and "to" point on the display area.

As described in these scenarios the user maintains a tight control in his prototype set and error correction interactions. As we learn more about the use of such recognition systems it may be possible to shift some of this control to the machine. For example, it may be possible to allow the user simply to edit the recognition results using standard editing symbols, and then have the machine correlate the indicated changes and, where there is sufficient evidence, appropriately revise the prototype set.

CONCLUSION

Much of interest has been learned by examining handwriting from the point of view of designing a machine recognition system. The range of variation in handwriting is wide. Even within a single sample of writing there can be substantial variation in character formation due to differences in stroke number, order, direction, and shape. As handwriting samples are examined in more detail and in large quantities from greater numbers of writers, we will be able to quantify the variation. Machine recognition provides an excellent vehicle for identifying variation since the exceptions are always highlighted.

The ultimate goal of this work is the machine recognition of unconstrained handwriting. Although the degree of writer variation is great, advances in algorithm development are encouraging, and we are confident that this goal can be attained. For minimally constrained handwriting, that is, where constraints are easily learned and conformed to, and errors recovered from, the outlook is even brighter.

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EXTRACTION OF THE ANALOG PENTIP POSITION, VELOCITY AND ACCELERATION SIGNALS FROM A DIGITIZER

Fadi Maamari
Réjean Plamondon

INTRODUCTION

Handwriting analysis relies on the solution of two kinds of problems: data acquisition and data processing. Although actual research activities are mainly engaged on the latter, certain restrictions still appear concerning the transducer to be used as input device for the data acquisition system, particularly in experiments aiming at real time commercial applications (automatic character recognition, signature verification or identification . . .). One restriction is the stability required on the transfer function of massproduced transducers. The function should not vary from one device to another; ideally, the same electrical output signals ought to result when a given pen movement is recorded on two identically built devices, or on the same device but at different periods of time. Another restriction concerns the reliability of the transducer: it should have a low breakdown probability.

Under these conditions digitizers seem to be very good displacement transducers, and efforts must be made to correct any difficulties that might arise from their utilization. Current high resolution digitizers provide the horizontal and vertical coordinates of the pentip position, generally at a sampling frequency around 100 Hz. It has been observed that this limited time resolution is too low for certain applications. Plamondon and Lamarche (1985) noted that a sampling rate of 100 coordinate pairs per second was not sufficient to enable the analysis of transient response characterizing the motor system involved in the handwriting process. Hollerbach (1981) using a Summagraphics ID Data Tablet/Digitizer at a sampling rate of 94 Hz and a spatial resolution of 0.1 mm., stated that accurate acceleration derivation could not be achieved because of the limited time and spatial resolution of the device.

This paper reports on a hardware solution to the problems of insufficient number of position coordinates per second and the inability to accurately derive pentip acceleration data in certain applications. The set up described in the following pages can be connected to the output of a digitizer to generate the analog pentip position, velocity and acceleration signals almost simultaneously. Limitations related to spatial resolution are also examined more closely; it is shown that although it still is the main source of noise in the derived signals, accurate results can be obtained when the time resolution is improved.

FEASIBILITY STUDY

The electronic system is based on the signal sampling and synthesis theory. If the frequency of a digitizer is greater than twice the highest frequency component of the sampled displacement signal, no loss of information occurs when the displacement signal is sampled, enabling the recuperation of the continuous analog displacement signal. The exact upper limit of the frequency spectrum of handwriting displacement signals is not known, and probably varies from one person to another. Vredenbregt and Koster (1971) observed no frequency component above 15 Hz. Dooijes [4] filters the displacement signal with a digital filter having a 13.6 Hz cutoff frequency, stating that any eventual signal component above that frequency would be well below the noise level of his set up. Hollerbach (1981) low-pass filtered the acceleration signals at 25 Hz, while Herbst and Liu (1977) used a digital filter with a half-power point of 22.5 Hz. It can thus be concluded that there are probably no significant frequency components above 20 Hz in handwriting displacement and acceleration signals (Teulings & Maarse, 1984). That conclusion can also be extended to velocity signals, as differentiation or integration does not generate new frequencies but respectively enhances and attenuates the power of existing high frequency components. The Nyquist frequency that the sampling rate of the digitizer must exceed in order to avoid any loss of information due to the sampling of the displacement signal is therefore around 40 Hz. The digitizer used in the project described in this paper is a SUMMAGRAPHICS MM 960, operating at a spatial resolution of 0.025 mm., or 40 lines per millimeter, and at a sampling frequency of 120 Hz, well above the 40 Hz mark. Consequently, the sampled data output of the digitizer contains all the information on the pentip displacement, and improvements to the time resolution of the displacement data are possible. This can be done by either digital or analog signal processing of the output displacement data of the digitizer.

A digital processing technique called 'oversampling' (Goedhart, Van de Plassche, Stikvoort, 1982) can be used to improve the time resolution of the digitizer: it consists of a digital filter operating at several times the sampling rate, delivering signal values at this increased frequency. The data that is fed to the filter at the increased frequency is composed of intermediate samples of zero values inserted between data samples. This technique is currently being used in digital compact discs, and custom VLSI chips have been designed to perform that task in real time at very high frequencies.

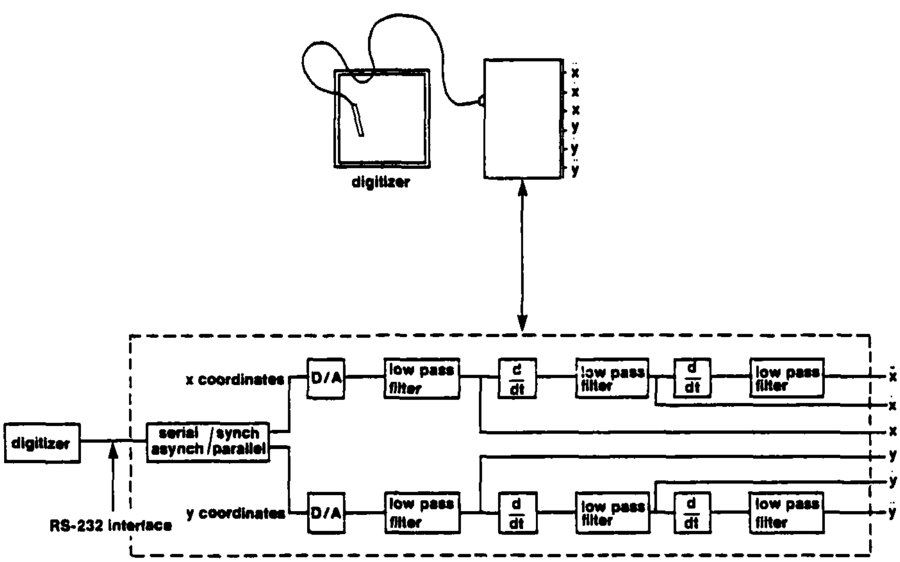
The highly improved time resolution that results enables the numerical computation of the velocity and acceleration data much more accurately than at the original sampling rate. The digital algorithms can be implemented with VLSI chips to compute the derivatives in real time, which is a great advantage. Another interesting feature of the oversampling process is that analog low-pass filtering of the oversampled data reduces the quantization noise power proportionally to the oversampling factor, suggesting that the combined use of analog and digital processing yields even better results.

The analog processing consists of the retrieval of the continuous displacement signal by low-pass filtering the staircase function obtained by sending the sampled digitizer data to a digital to analog converter, enabling the derivation of the velocity and acceleration signals by analog differentiation. For reasons of cost and simplicity, this analog approach was chosen and is presented in the following sections.

SYSTEM OVERVIEW

A block diagram of the system developed in our laboratory is presented in Figure 1. The digitizer, as mentioned earlier, is a Summagraphics MM 960. It has an active area of 6"×9" inches that represents a cartesian plane where X and Y coordinates identify points on the surface that correspond to the location of a pentip. Whenever the pentip is within one half inch of

Figure 1 Block diagram of the system



the active surface of the digitizer, the device transmits 120 coordinate pairs per second on an RS-232C serial bus. The asynchronous serial data received by the system is then converted to synchronous parallel format, and the X and Y coordinates are separated; from there on they are simultaneously processed on two separate but identical channels. The coordinates are fed in parallel format to digital to analog converters at the sampling rate of the digitizer, resulting in staircase like displacement functions. The functions are then low-pass filtered with eighth order Bessel filters having a cut-off frequency of 20 Hz. Phase distortion is maintained at a negligible level throughout the system, but the use of Bessel filters results in a slight attenuation in the upper frequencies (approximately – 0.7 dB @ 10 Hz for each filter). The resulting continuous displacement signals are differentiated to yield the pentip velocity and acceleration signals. Fourth order Bessel filters with a cut-off frequency of 18.5 Hz eliminate high frequency noise after each differentiation. The resulting online system outputs are the vertical and horizontal projections of the pentip displacement, velocity and acceleration.

METHOD

The time function and frequency spectrum of the displacement signal at different steps in the sampling and reconstruction process is illustrated in Figure 2, using as an example a bandlimited signal $f_1(t)$ (figure 2a) having a uniform frequency spectrum, $S_1(f)$ (figure 2b). When $f_1(t)$ is sampled at a frequency of 100 Hz, as usually done by a digitizer, it is in fact multiplied by a Dirac comb $\delta_T(t)$, of period T = 0.01, resulting in the function.

$$f_2(t) = f_1(t)\,\delta_{0.01}(t) = f_1(t) \sum_{n=-\infty}^{\infty} \delta(t - 0.01n) \tag{1}$$

(fig. 2c)

with the frequency spectrum

$$S_2(f) = S_1(f) * F[\delta_{0.01}(t)] \tag{2}$$

where $F[\delta_{0.01}(t)]$ is the Fourier transform of the Dirac comb;

$$S_2(f) = S_1(f) * 100 \sum_{n=-\infty}^{\infty} \delta(f - 100n) \tag{3}$$

$$S_2(f) = \sum_{n=-\infty}^{\infty} S_1(f - 100n) \qquad \text{(fig. 2d)} \tag{4}$$

Although the function $f_2(t)$ accurately represents the sampled data, it cannot exist as an analog electrical signal because its energy would be infinite:

$$E = \int_{-\infty}^{\infty} |S_2(f)|^2\, df = \infty \tag{5}$$

This problem can be solved by holding the value of the last sample; the resulting function $f_3(t)$ (figure 2e) is constructed in the real system by the D/A converter, and corresponds theoretically to the result of the convolution of $f_2(t)$ to a rectangular pulse g(t) that has a 0.01 s width:

$$g(t) = \begin{cases} A & |t| \leqslant 0.005s \\ O & |t| \leqslant 0.005s \end{cases} \tag{6}$$

The resulting frequency spectrum of f3(t) is

$$S_3(f) = S_2(f)\, F[g(t)] \tag{7}$$

where F[g(t)] is the Fourier transform of g(t);

$$S_3(f) = S_2(f)\ A\ \frac{\sin(0.01\,\pi f)}{\pi f} \tag{8}$$

$$S_3(f) = K\, S_2(f)\ \frac{\sin(0.01\,\pi f)}{\pi f} \qquad \text{(fig. 2f)} \tag{9}$$

where K is a constant. A low-pass filter, shown with a dashed line in figure 2f, eliminates the upper frequencies, leaving only the baseband spectrum

$$S_4(f) = \begin{cases} K\, S_1(f)\ \dfrac{\sin(0.01\,\pi f)}{(0.01\,\pi f)} & |f| \leqslant 20\ \text{Hz} \\ 0 & |f| > 20\ \text{Hz} \end{cases} \qquad \text{(fig. 2h)} \tag{10}$$

In the 0 to 20 Hz range, the factor $\sin(0.01\,\pi f)/(0.01\,\pi f)$ is approximately equal to one:

$$\frac{\sin(0.01\,\pi f)}{(0.01\,\pi f)} = \begin{cases} 1.00 & 0\ \text{Hz} \leqslant f \leqslant 5\ \text{Hz} \\ 0.99 & f = 9\ \text{Hz} \\ 0.98 & f = 12\ \text{Hz} \\ 0.94 & f = 20\ \text{Hz} \end{cases} \tag{11}$$

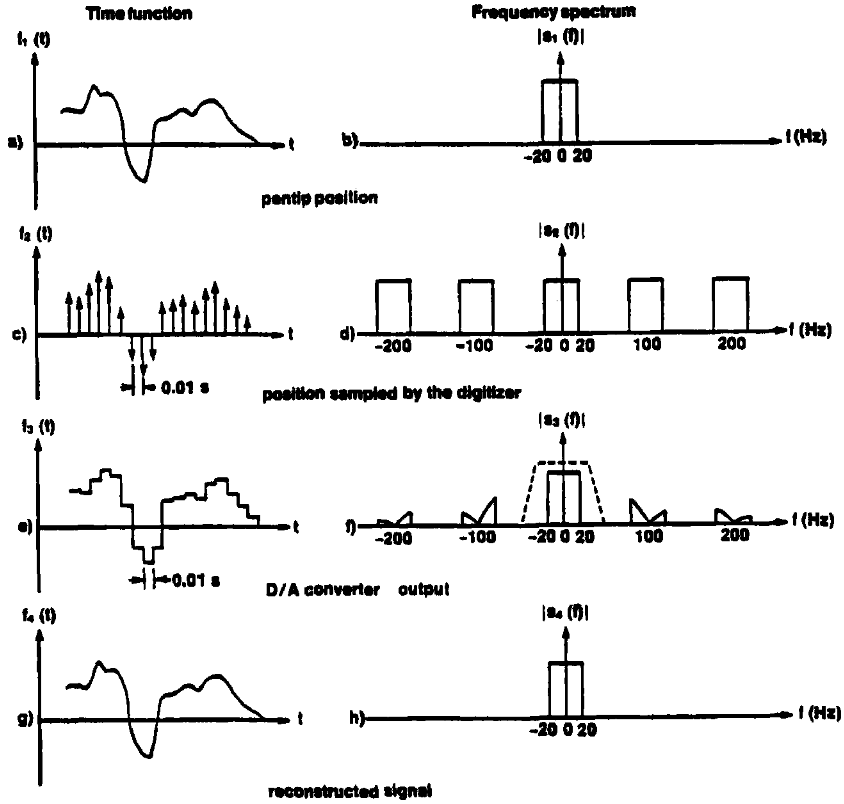
That leads to

$$S_4(f) \approx K\, S_1(f) \tag{12}$$

$$f_4(t) \approx K\, f_1(t) \qquad \text{(fig. 2g)} \tag{13}$$

The initial analog signal has thus been recovered, with a slight attenuation in the upper frequencies that can eventually be compensated with an equalizing filter in applications where a higher accuracy is needed.

Figure 2 Time function and frequency spectrum of the position signal at different steps in the sampling and reconstruction process.



NOISE ESTIMATES

There are some limitations in the real system that add a certain amount of noise to the recovered displacement signal. The main noise contributing factor is the limited spatial resolution of the digitizer that generates quantization noise in the sampled displacement data. Another is the nonlinearity error of the digital to analog converter. Upper limits for the quantization and nonlinearity errors are given by the manufacturers and are expected to remain valid on a long term basis. The noise generated in the rest of the analog processing is kept well below the quantization noise level by a careful choice of components in the circuit design, and is therefore negligible.

An estimate of the quality of the signal can be done by evaluating the signal to noise power ratio of the recovered displacement signal. Let Δ be the step size of the least significant bit (LSB). For signals of sufficient amplitude and complexity, there is no correlation between the quantization errors of two consecutive samples. $d_1(\epsilon)$, the probability density of the quantization noise, can therefore be considered uniformly distributed between $-\Delta$ and Δ, the limits specified by the manufacturer of the digitizer; for the SUMMAGRAPHICS MM960, Δ=0.025 mm.

$$d_1(\epsilon) = \begin{cases} \dfrac{1}{2\Delta} & |\epsilon| \leqslant \Delta \\ 0 & |\epsilon| > \Delta \end{cases} \quad (14)$$

The nonlinearity error of the D/A converter is specified at ± 1/2 LSB, but its probability density is not known. We chose to consider it uniformly distributed over the $-\Delta/2$ to $\Delta/2$ interval for our calculations:

$$d_2(\epsilon) = \begin{cases} \dfrac{1}{\Delta} & |\epsilon| \leqslant \dfrac{\Delta}{2} \\ 0 & |\epsilon| > \dfrac{\Delta}{2} \end{cases} \quad (15)$$

The noise in the recovered displacement signal is the sum of the quantization noise and the nonlinearity error of the D/A converter; its probability density is therefore given by

$$d_3(\epsilon) = d_1(\epsilon) * d_2(\epsilon) \quad (16)$$

$$d_3(\epsilon) = \begin{cases} \dfrac{1}{2\Delta} & |\epsilon| \leqslant \dfrac{\Delta}{2} \\ -\dfrac{1}{2\Delta^2}|\epsilon| + \dfrac{3}{4\Delta} & \dfrac{\Delta}{2} \leqslant |\epsilon| \leqslant \dfrac{3\Delta}{2} \\ 0 & |\epsilon| \geqslant \dfrac{3\Delta}{2} \end{cases} \quad (17)$$

The RMS value of the noise is given by

$$\epsilon_{RMS} = \left[\int_{-3\Delta/2}^{3\Delta/2} \epsilon^2 \, d_3(\epsilon) \, d\epsilon \right]^{\frac{1}{2}} \quad (18)$$

$$\epsilon_{RMS} = \left[\frac{5\Delta^2}{12} \right]^{\frac{1}{2}} \quad (19)$$

If n bits are used to quantify the signal, its maximum peak to peak value will be $2^n\Delta$. A sinusoid of maximum amplitude will have an RMS value of:

$$V_{RMS}^{(max)} = \frac{2^n\Delta}{2\sqrt{2}} \quad (20)$$

The resulting signal to noise power ratio for that signal is

$$\frac{S}{N} = 10 \log \left[\frac{2^{2n}\Delta^2}{8} \times \frac{12}{5\Delta^2} \right] \tag{21}$$

$$\frac{S}{N} = -5.23 + 6.02\,n \tag{22}$$

At the resolution of 40 lines per millimeter, nine bits are used to quantify the vertical displacement of the pentip in a handwritten pattern with a height of 13 mm., resulting in a signal to noise ratio of 49 dB. It rises to 55 dB for a height of 26 mm., and stands at 43 dB for a height of half a centimeter. These results were verified experimentally by quantifying the signal with a 12 bit A/D converter that introduced a supplementary quantization error of $\pm \Delta/2$, reducing the expected S/N ratio to

$$S/N = 6.02\,(n - 1). \tag{23}$$

The noise, situated in the $\pm\ 2\Delta$ range, was observed by immobilizing the pen at different positions on the digitizer with a clamp, eliminating the trembling that results when the pen is held by hand. It should be noted that a good part of the quantization noise power lies outside the signal bandwidth and is eliminated by the low-pass filtering; the S/N power ratio calculated in (22) is therefore somewhat conservative.

Signal to noise power ratios for the velocity and acceleration signals are difficult to calculate theoretically because the variations encountered in the frequency spectrum of the displacement signals of different persons preclude the precise estimation of the amplitude of the differentiated signals. Usually, the upper frequency content of the handwriting displacement signals are weak, resulting in a smaller S/N power ratio in the differentiated signals than the one observed for the displacement signals. In the absence of upper frequency content in a handwriting signal, the deterioration can be reduced by low-pass filtering the differentiated signals with a lower cut-off frequency. Experimental values of the resolution of the differentiated signals are obtained by measuring their step response: the step simulates the jitter of the digitizer and is generated by changing the value of only one bit of the A/D converter. Considering a displacement signal accuracy of $\pm 2\Delta$, the following results were obtained:

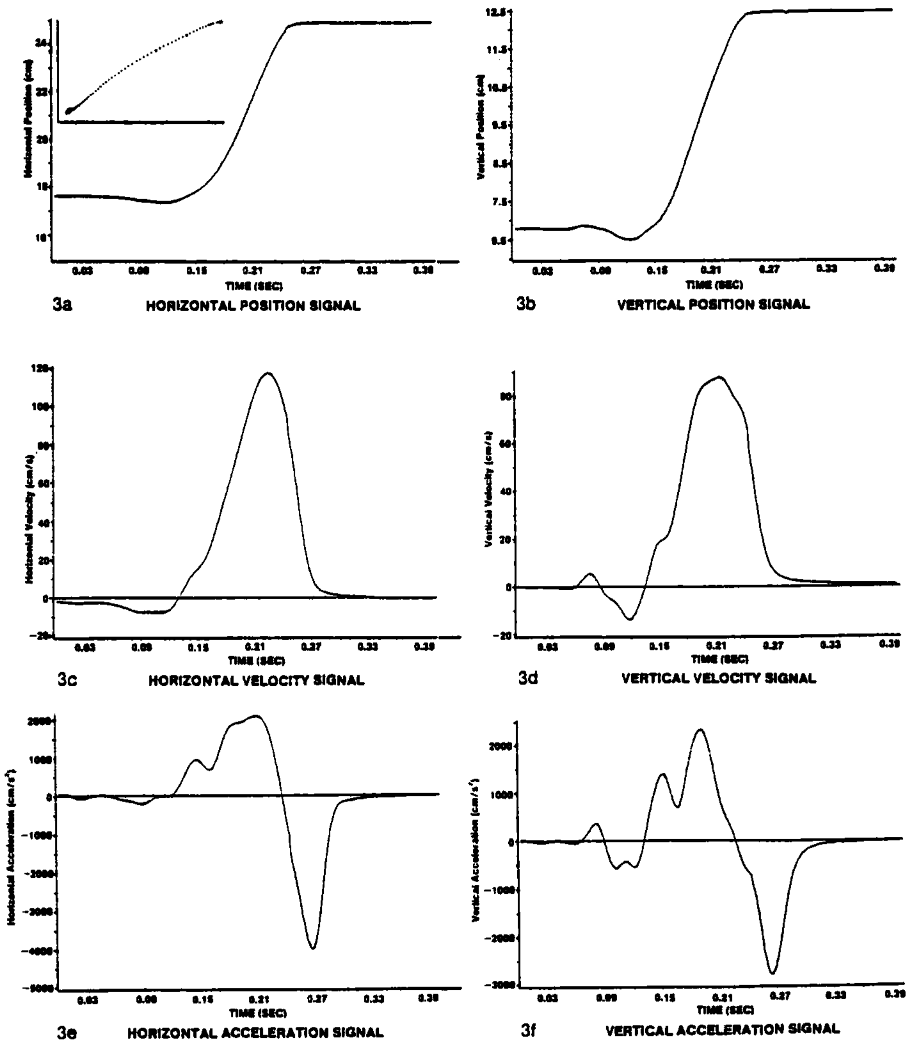
displacement resolution:	± 0.005 cm	(24)
velocity resolution:	± 0.54 cm/s	(25)
acceleration resolution:	± 30 cm/s^2	(26)

Typical values for signals resulting from handwritten initials were observed to go up to approximatly 50 cm/s in velocity and 1500 cm/s^2 in acceleration.

Outputs

On line horizontal and vertical pentip displacement, velocity and acceleration signals are generated with a delay of 12 ± 0.2 msec. for each differentiation. The delay was measured and observed to be constant over

Figure 3 System outputs for a diagonal stroke.



the 0-20 Hz signal bandwith, as a result of the use of linear phase (Bessel) filters. The presence of that delay necessitates the time shift of the sampled differentiated signals if a direct comparison of the position, velocity and acceleration signals is to be made. Since the A/D sampling frequency is finite, the possible discrete time shifts might not correspond to the real analog delay. This difficulty can be overcome by either using a high sampling frequency or matching the sampling frequency to the delay. For the observed 12 msec. delay, examples of adequate sampling frequencies are 41.7, 83.3,

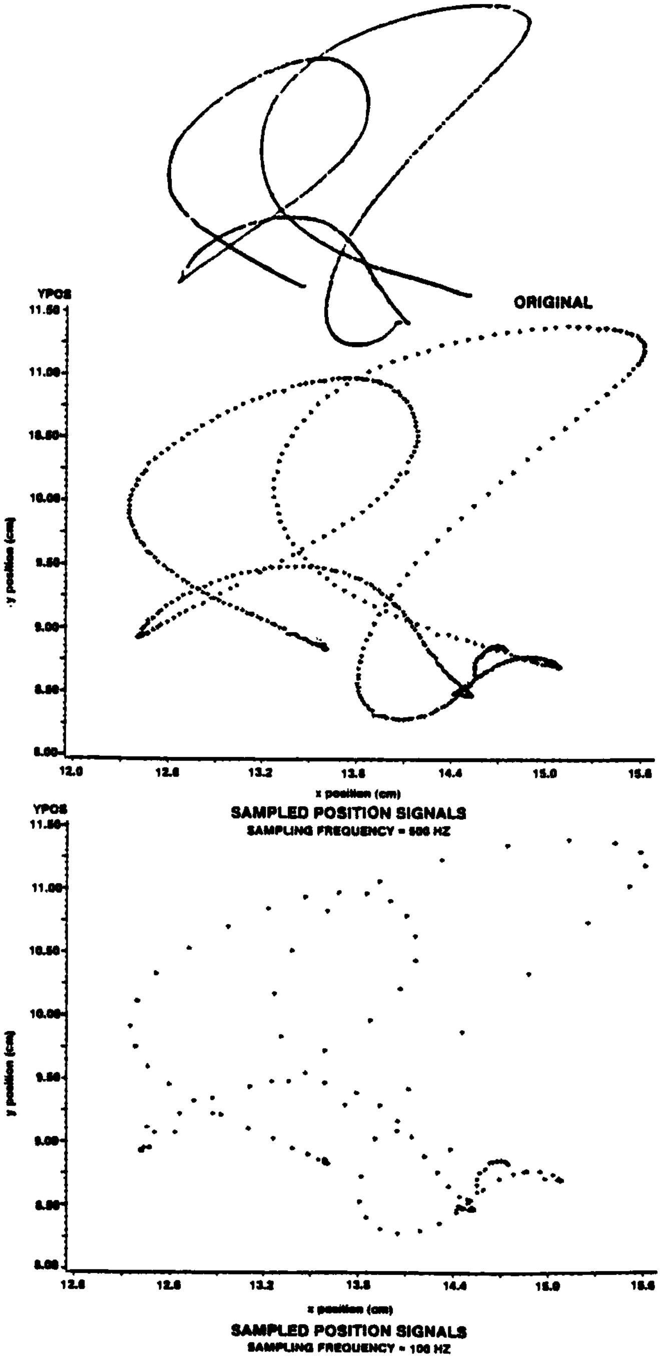
167, 250, 333 and 500 Hz. An example of outputs is shown in Figure 3 for a stroke written diagonally on the digitizer. The stroke, sampled at 500 Hz, is insetted in Figure 3. The differentiation process and the resulting 12 msec. time shift are clearly visible; as expected, the velocity rises to a peak and then returns to zero, while the acceleration passes through a positive and a negative peak, reflecting the forces that were applied to start and stop the movement. An example of acquired data for handwritten initials is shown in Figures 4 and 5. In Figure 4, an accurate match is observed when the original initials are compared to the position samples acquired at frequencies of 500 Hz and 100 Hz, the latter being the usual sampling rate of digitizers. The only notable difference occurs when the pentip is not in contact with the paper between the 'R' and 'P' initials, causing an interruption of the writing that can be seen on the bottom right of figure 4a. During that period, as long as the pentip remains within a half inch distance (characteristic of the SUMMAGRAPHICS MM960) of the active digitizer surface, its position continues to be sampled and therefore appears on the bottom right of figures 4b and 4c. This half inch limit appears to be sufficient for most handwriting studies. The six output signals shown in Figure 5 contain the static and dynamic information that is needed for handwriting analysis purposes.

DISCUSSION

The apparatus described in this paper presents several advantages suggesting its use as a general purpose data acquisition tool for handwriting applications. It is easy to use since it interfaces directly to the RS-232-C output cable of a digitizer and only requires an A/D conversion module on the computer side. The set up can function with any commercially available digitizers that have sufficient time and spatial resolution ($F \geqslant 100$ Hz, $\triangle \leqslant 0.025$ mm.). Only slight changes might have to be made on the serial asynchronous to parallel synchronous converter to take into account the different output format of these devices. Tests using a freezing spray on the circuit to evaluate its temperature sensitivity showed no significant change in the 12 msec. differentiation delay, but the amplitude of the signals was affected by large temperature variations. However, as the system was designed for indoor use, temperature compensation of the analog circuitry was omitted.

When connected to a digitizer, the analog pentip, velocity and acceleration signals are generated almost instantaneously, giving an immediate description of the dynamics of the handwriting movement that is taking place; these outputs are measured in an inertial reference system, as opposed to the moving reference system that results in systems where transducers such as accelerometers are integrated in a pen. The simultaneous availability of this information might be of practical interest in experiments dealing with handwriting analysis and synthesis. Such a set up could also be used in signature verification systems to minimize the algorithmic preprocessing of dynamic features often used in these systems (Zimmerman 1978).

Figure 4 Example of original and recovered position signals.

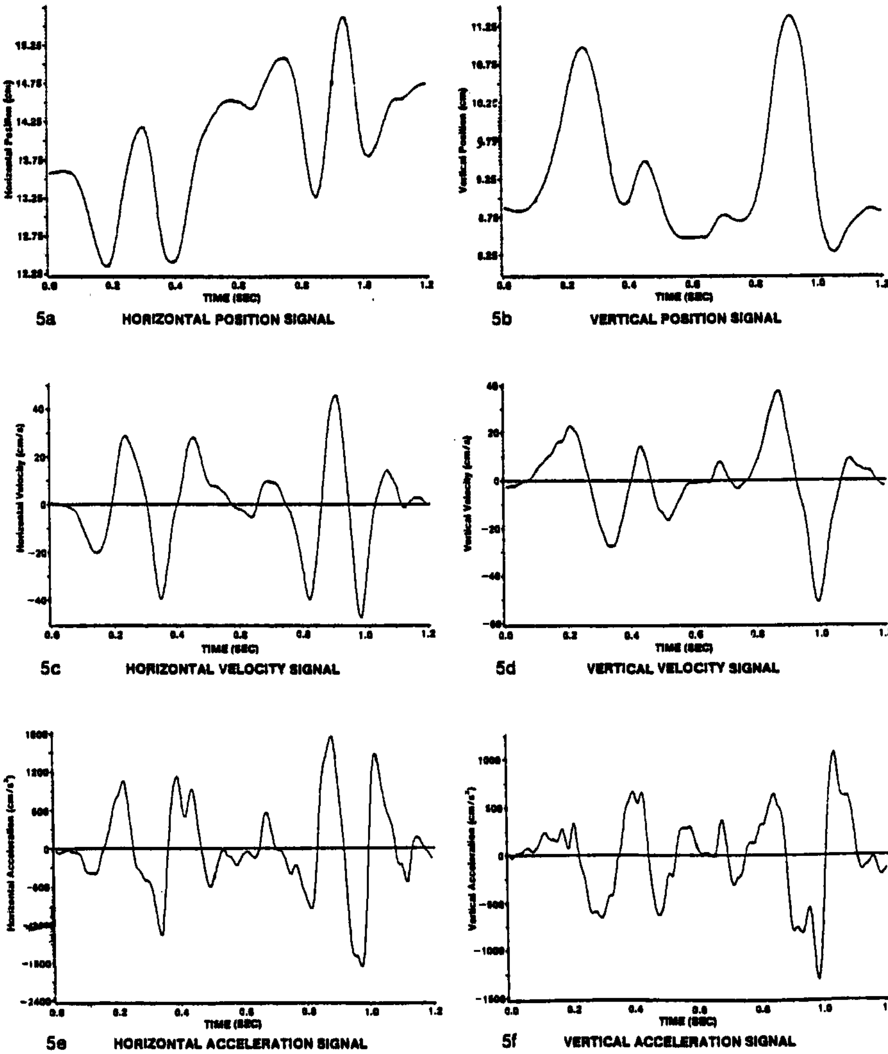


4a

4b

4c

Figure 5 System outputs for initials of Figure 4.



The output signals can be sampled at a higher rate than the 100 Hz commonly available from digitizers. This has been proved very useful for studies on the transient response of the biomechanical handwriting system and might also be of interest for some character recognition applications where the number of points available from one character often limits the recognition rate of the algorithm. One must however remember that working at a higher sampling rate will require a larger buffer in the computer memory and will result in a longer processing time. Another advantage of the method is its independency of the digitizer sampling frequency. Since most digitizers were not designed for movement studies, they sometimes have odd sampling rates, such as 105.2 Hz.

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HUMAN RECOGNITION OF HANDPRINTED CHARACTERS AND DISTANCE MEASUREMENTS

C. Y. Suen

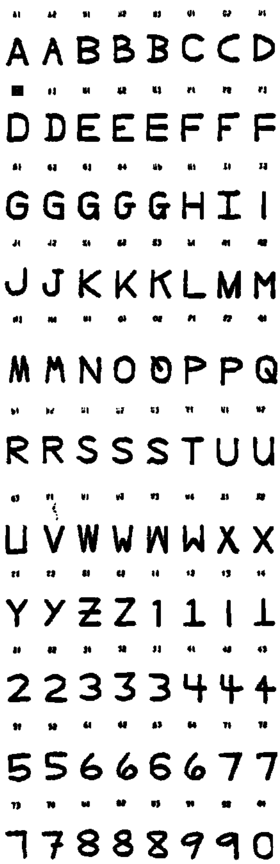
INTRODUCTION

Human beings learn to distinguish and recognize different characters and symbols during their childhood. As they read and write more, they acquire a high degree in recognizing a great variety of shapes representing characters written by many people including the poor writers. Legibility tests with human subjects indicate that different styles and shapes of characters, and different characters of the alphabet have different degrees of legibility. (Geyer, et al., 1981; Poulton, 1965; Suen, 1983). Poor handwriting and distorted character shapes are the sources of many cases of inconvenience, frustration, and misunderstanding.

In search of the most legible and distinct set of handprinted characters (block printing) for efficient communication, the author has collected a large number of handprint shapes from over 30 handwriting systems taught in most schools in North America (Suen, 1983 & 1986). Two approaches were taken to identify the most distinctive handprinted letters of the Roman alphabet, i.e., (1) legibility tests with 12,180 presentations to subjects using a tachistoscope, and (2) distance measurements. In the distance measurements, all models of letters and numerals (e.g., letter G has 5 models: G, G, G, G, G) were digitized by an optical scanner and normalized to a uniform size of 29 wide by 39 cells high. The high resolution of 29×39 is used in order to preserve the original shapes of the characters to approach letter quality (Geyer, et al., 1981). These characters were measured by 10 distances, viz. 3 similarity functions, 2 information measurements, and 5 comparisons of the matrix configurations of characters (Suen, et al., 1980). Each measurement gives the distances between the character model and the other models, from which distinctiveness of the model can be ranked. Correlation between legibility and all the distances was computed and analyzed. The ranks of the character models were also compared with the results of the legibility tests.

In preparation of the set of handprint alphanumeric models, an extensive review of the handwriting systems taught in elementary schools and in the computer industry was conducted by Suen (1983). In this investigation, more than 30 different handwriting systems were studied and the models proposed by ANSI (Suen, 1986) and various OCR manufacturers were also examined. Altogether, 87 different models of the 36 alphanumeric symbols were assembled. They comprised 60 models of letters and 27 models of numerals. The numeral 0 is not counted because it is identical to one model of the letter "oh." These alphanumeric models are presented in Figure 1. Each model was coded into a binary matrix of 29 columns and 39 rows. This operation brings all characters to the same width and height in order to eliminate any effect due to size variations. For simplicity, C_{ij} will be used to indicate the ij-th cell of model C and $C_{ij}=1$ if the ij-th cell of C is "occupied" and $C_{ij}=0$ if otherwise.

Figure 1 Character models used in this study each with a matrix size of 29 × 39.



METHOD

Subjects

Twenty paid subjects with ages ranging from 18 to 30 were drawn from the university community. Fourteen of them required corrective lenses.

Materials

The shapes of the character models are shown in Figure 1. Each model was presented in a 0.16" × 0.24" rectangle on a white 5" × 7" card. A number of samples served as practice stimuli for all subjects.

The experiment was conducted in a darkened room. Illumination was provided by a desk lamp pointing upwards near a wall. The stimuli were exposed one at a time for identification using one channel of a three channel tachistoscope (Scientific Prototype Co., Model GB). A blank 5" × 7" card with a 0.5" × 0.75" rectangle cut in the centre served as background. All subjects were told to fix their eyes on this area prior to the exposure of characters.

Procedure

Subjects were tested individually. Prior to the test, they were given 5 practice trials to become acquainted with the test procedure. The practice stimuli included an unfamiliar character Ȍ ("oh"). The 27 selected numerals and 60 letters were presented alternately in random order via the tachistoscope. When exposed, the character appeared in the center of the rectangle in the background. The task of the subjects was to correctly identify the exposed character and they were discouraged from guessing. A ready signal was used to indicate the start of each trial. Guided by the results of pilot tests, the initial exposure time was set at 6 ms. and increased at intervals of 4 ms. until correct identification was attained. The required exposure time was recorded and incorrect responses were also noted for later evaluation of character confusions. The entire experiment took about 1 hour and 45 minutes. Subjects were given rests in-between.

RESULTS

Legibility of these characters was also ranked according to the exposure time required for correct identification. The scores indicate that numerals are more legible than the letters. The average exposure time for the 10 most legible numerals is 21.34 ms./character compared with 23.45 ms./character for the 26 most legible letters. Moreover, the average exposure of the whole set of 27 numerals is shorter than the average for the 60 letters, i.e., 22.82 ms. against 25.96 ms. This may be attributed to the fewer number of numerals and their relatively simpler structure. The small difference between average legibility scores of the most legible 36 characters and the entire set of 87 characters suggests that most characters which are clearly written can be recognized regardless of form. In fact, an analysis of variance of the data shows that only three groups of characters (C, D and Q) have significant differences (probability <0.05) within their groups.

Table 1 Measurements of the five models of the letter G.

Measurements	Model G1	Model G2	Model G3	Model G4	Model G5
AVE(AND, ,*)	123.9	128.4	130.6	101.6	111.6
AVE(XOR, ,*)	312.0	328.0	340.5	331.5	354.6
AVE(LA,)	43.6	43.2	42.7	37.5	38.1
AVE(CA,)	23.3	22.3	21.9	16.9	17.0
INF( )	2636.7	2900.4	3093.4	2480.4	2920.9
ENT( )	4.1	4.3	4.4	3.4	3.7
AVE(MID1,,*)	4.6	4.7	4.7	5.2	4.9
AVE(MID2,,*)	5.2	5.3	5.2	5.4	5.3
M( )	9.3	9.3	9.0	9.3	9.4
CG( )	0.5	2.4	2.7	2.5	3.0

Distance Measurements and Distinctiveness of Characters

The ten measurements we used were obtained from the average values of the following functions: (1) similarity function, (2) hamming distance, (3) linear correlation function, (4) cross correlation function, (5) information content, (6) entropy, (7) nearest neighbor distance-1, (8) nearest neighbor distance-2, (9) Mahalanobis distance, and (10) centre of gravity.

By using each of the above functions, measurements were made between each model and the remaining models in the alphanumeric set, taken two at a time. These measurements were summed and averaged (Suen, et al., 1980). The 10 averages (or sums) of different models of the same symbol (e.g., the symbol "G" has 5 models G1, G2, G3, G4 and G5 in the alphanumeric set of 87 models shown in Figure 1) were computed.

Similarity Function

The similarity function A(C,D) was used to measure the number of matrix cells "occupied" by both models C and D. It is given by the following formula:

$$A(C,D) = \sum_{i=1}^{29} \sum_{j=1}^{39} (C_{ij} \text{ .AND. } D_{ij}) \text{ where}$$

$$C_{ij} \text{ .AND. } D_{ij} = \begin{cases} 1, & \text{if the ij-th cell is "occupied" by both models C and D,} \\ 0, & \text{otherwise.} \end{cases}$$

The smaller the value of A(C,D) is, the less the "common area" is shared by models C and D, and therefore the less the degree of "similarity" between the two models.

Two average measurements were obtained. One calculated the average value of the operation A(C,D) of model C with respect to each model D of the remaining models in the alphanumeric set. It can be expressed by the equation:

$$AVE(AND,C) = \left(\sum_{D \epsilon S(C)} A(C,D) \right) / (N-1) \text{ where}$$

S (C) is the subset of the alphanumeric set S without model C, and N is the number of models in the entire set S. The other measured the average value of the similarity function A(C,D) of model C with respect to all models of different symbols in the alphanumeric set. It can be expressed by the equation:

$$AVE(AND,C,*) = \left(\sum_{D \epsilon S(C,*)} A(C,D) \right) / N(C,*) \text{ where}$$

S(C,*) is the subset of the alphanumeric set S less all models which belong to the same symbol C and N(C,*) is the number of models in the subset S(C,*). A larger value of AVE(AND,C,*) (or AVE(AND,C)) indicates that the total "common area" shared by the model C and all models of *different* symbols (or the model C and the remaining models in the set) is larger and therefore less desirable. Since consistent results were obtained from these two average measurements, only the measurement AVE(AND,C,*) was used in the evaluation.

Hamming Distance

The Hamming distance X(C,D) was used to measure the number of different cells occupied by the two models C and D. It is given by the following formula:

$$X(C,D) = \sum_{i=1}^{29} \sum_{j=1}^{39} (C_{ij} \text{ .XOR. } D_{ij}) \text{ where}$$

$$C_{ij}.XOR.D_{ij} = \begin{cases} 1, & \text{if the ij-th cell is occupied by one model and not by the other of the two models C and D,} \\ 0, & \text{otherwise.} \end{cases}$$

The larger the value of X(C,D) is, the greater the "difference" between the models C and D. As was in the case of the Similarity Function, two average measurements were obtained and only the measurement AVE(XOR,C,*) which calculated the average value of the operation X(C,D) of model C with respect to all models of different symbols in the alphanumeric set was used in the evaluation. A smaller value of AVE(XOR,C,*) indicates that the "difference" between model C and models of *different* symbols is smaller and therefore is less desirable.

Linear and Cross Correlation Functions

Taking into consideration the various degrees of misalignment and stroke width variation of models, the similarity function A(C,D) was modified to obtain two new measurements. The linear correlation function LA(C.D) was obtained by dividing A(C,D) by the arithmetic mean of the number of cells occupied by models C and D. It is given by the equation:

$$\begin{aligned} LA(C,D) &= A(C, D) / ((N_C+N_D) / 2) \\ &= 2(A(C,D) / (N_C+N_D)) \text{ where} \end{aligned}$$

N_C and N_D are numbers of cells occupied by models C and D respectively. The cross correlation function CA(C,D) was obtained by taking the square of the quotient of the measurement A(C,D) and the algebraic mean of the number of cells occupied by models C and D. That is,

$$\begin{aligned} CA(C,D) &= (A(C,D) / (N_C.N_D)^{1/2})^2 \\ &= (A(C,D))^2 / (N_C.N_D). \end{aligned}$$

Each of these two measurements gives us a normalized area correlation between models C and D.

Two magnified average measurements were obtained by using these two correlation functions. They are given by the following equations:

$$\begin{aligned} AVE(LA,C) &= (\frac{1}{N}(\sum_{D \epsilon S} LA(C,D))).N \\ &= \sum_{D \epsilon S} LA(C,D) \\ &= \sum_{D \epsilon S} 2(A(C,D) / (N_C.N_D)) \end{aligned}$$

and

$$\begin{aligned} AVE(CA,C) &= (\frac{1}{N}(\sum_{D \epsilon S} CA(C,D))).N \\ &= \sum_{D \epsilon S} CA(C,D) \\ &= \sum_{D \epsilon S} ((A(C,D))^2 / N_C.N_D). \end{aligned}$$

A smaller value of AVE(LA,C) (or AVE(CA.C)) indicates that the normalized common area shared by the model C and all models in the entire set S is smaller. Consequently, among models of the same symbol, the one with the smallest value of AVE(LA,) (or AVE(CA,)) is preferred. Both measurements AVE(LA,) and AVE(CA,) were used.

Information Content and Entropy

For each model C of the alphanumeric set S, the information content and entropy measurements are given by the following equations:

$$INF(C) = \sum_{i=1}^{29} \sum_{j=1}^{39} (I_{ij}.C_{ij}) \text{ and}$$

$$ENT(C) = \sum_{i=1}^{29} \sum_{j=1}^{39} (P_{ij}.I_{ij}.C_{ij}) \text{ where}$$

P_{ij} = probability of the ij-th cell being occupied by all models in the alphanumeric set,

I_{ij} = $-\log_2 P_{ij}$ and

$$C_{ij} = \begin{cases} 1, & \text{if the ij-th cell is being occupied by model C,} \\ 0, & \text{otherwise.} \end{cases}$$

The information content INF(C) is a measure of the information carried by cells of model C based on the distribution of the entire set of models and the entropy ENT(C) is a measure of the average information content carried by model C. Thus among models of the same symbol, the one with the smallest value of INF( ) (or ENT ( )) is preferred.

Nearest Neighbor Distances

The "nearest cell distance" $d(C_{ij},D)$ was used to measure the "distance" between the ij-th cell of model C and the nearest cell occupied by model D. It is given by the following formula:

$$d(C_{ij},D) = \begin{cases} 0, \text{ if } C_{ij} = 0, \\ \min_{\substack{1 \leq m \leq 29 \\ 1 \leq n \leq 39}} \{(m-i)^2 + (n-j)^2 + | D_{mn} \neq O\}, \text{ if } C_{ij} \neq 0 \end{cases}$$

Obviously, a larger value of $d(C_{ij},D)$ indicates a larger "distance" between the cell C_{ij} and the "nearest cell" occupied by the model D.

For any pair of models C and D, two measurements were obtained and used to indicate the degree of difference between the pair. They are given by the following equations:

$$MID1(C,D) = \frac{1}{N_C} (\sum_{i=1}^{29} \sum_{j=1}^{39} (d(C_{ij},D))_{1/2} +$$

$$\frac{1}{N_D} \sum_{i=1}^{29} \sum_{j=1}^{39} (d(D_{ij},C))^{1/2})$$

and

$$MID2(C,D) = (\sum_{i=1}^{29} \sum_{j=1}^{39} (d(C_{ij},D)/N_C +$$

$$\sum_{i=1}^{29} \sum_{j=1}^{39} d(D_{ij},C)/N_D)^{1/2}$$

A larger value of the "nearest neighbor distance-1" MID1(C,D) (or the "nearest neighbor distance-2" MID2(C,D) indicates that the "cell-difference" between the models C and D is greater.

Two average measurements were obtained by using the two nearest neighbor distances. They are given by the following equations:

$$AVE(MID1,C,*) = \sum (D \epsilon S(C,*)\ MID1\ (C,D))\ /\ N(C,*).$$

and

$$AVE(MID2,C,*) = \sum (D \epsilon S(C,*)\ MID2(C,D))\ /\ N(C,*).$$

Clearly, a larger value of AVE(MID1,C,*) (or AVE(MID2,C,*)) indicates that the model is more "distinct" against the models of different symbols. Consequently, among models of the same symbol, the one with the largest value of AVE(MID1, ,*) (or AVE(MID2, ,*)) is preferred.

Mahalonobis Distance

This distance is given by the following equation:

$$N = (C - \overline{m})'C_v^{-1}(C - \overline{m})$$

where C is a matrix model in the set S, $\overline{m}$ is the mean vector of the set, C_v is the covariance matrix of the set. The larger the distance from other symbols, the more distinct is the character in the set.

Centre of Gravity

This was used to find the distance of the centre of gravity (CG) of the characters. Its value indicates whether the character shape is symmetrical or not, or its density (hence its structure) is biased towards any particular direction. The co-ordinates of the centre of gravity are given by the following equation:

$$CG = \frac{\sum_{i=1}^{B} x_i}{B}, \frac{\sum_{i=1}^{B} y_i}{B}$$ where

x_i = the x-co-ordinate of C_{ij}
y_i = the y-co-ordinate of C_{ij}
B = total number of black elements in the character matrix

The further the CG is away from the mean population, the more distinct the character is in the set.

Table 2 Legibility of the five models of the letter G expressed in ms. of exposure time required to identify the character correctly.

	Model G1	Model G2	Model G3	Model G4	Model G5
Legibility	25.8	26.2	20.4	31.2	27.4

Analyses

In order to see whether humans make use of any of the distance measurements in character recognition, correlations between legibility and distance measurements were computed using Pearson's product-moment coefficients of correlation. The results are presented in Table 3. As expected from the mathematical formulae, some distance measurements have strong correlation with each other, in particular the following:

AND and CA: correlation coefficient 0.8962, $p<0.1$
AND and LA: correlation coefficient 0.9412, $p<0.1$
CA and LA: correlation coefficient 0.9749, $p<0.1$
MID1 & MID2: correlation coefficient 0.9600, $p<0.1$

Also, entropy ENT which depends on the probability density of the cells in the 29x39 matrix, has a strong correlation with the linear correlation measure LA (correlation coefficient 0.9980, $p<0.1$), the cross correlation measure CA (correlation coefficient 0.8717, $p<0.1$), and LA (correlation coefficient 0.9231, $p<0.1$).

On analyzing the correlation between human recognition and all 10 distance measurements, it was found that none of the distances is strongly correlated to human recognition. This may suggest that humans do not make use of purely one particular distance measurement to recognize characters, but it's more likely that they make use of a number of them together with other cues which have not yet been investigated here, to recognize the characters correctly. Further analysis indicates that this is a strong possibility, e.g., the LA distance gives the same results as the humans for characters which are formed from simple bays like C, J, V; and the Mahalanobis distance M for characters composed of an upper bay facing the west like I, Z, 1, 2, and 3.

Table 3 Pearson's product-moment coefficients of correlation between legibility scores and distance measurements, and among distance measurements.

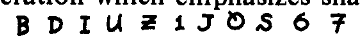
	AND	XOR	CA	LA	ENT	INF	MID1	MID2	M	CG
Legibility	.139	-.026	.132	.123	.141	.088	-.048	-.083	-.083	-.127
AND		-.169	.896	.941	.998	.650	-.751	-.582	.190	-.203
XOR			-.561	-.473	-.117	.639	-.165	-.289	.227	-.339
CA				.975	.872	.267	-.524	-.340	-.027	-.045
LA					.923	.370	-.628	-.429	.130	-.037
ENT						.688	-.766	-.602	.204	-.221
INF							-.716	-.680	.325	-.421
MID1								.960	-.352	.518
MID2									-.264	.651
M										.086

On examination of the collected data using a different analysis, the distances of various measurements of the various models of the characters were ranked and compared with those which gave the highest legibility. For example, in Table 1, AND and XOR ranked the models G3 and G5 respectively as the most distinct models among all 5 different shapes of G. This results in the ranking distributions presented in Table 4. From this table, we can see that LA has 19 models out of 36 ranked the same as the humans (A1, B3, E2, etc.), while CG produced the least number (15) of models in agreement with the legibility results. These figures again show that the human beings do not make use of only one particular distance measurement in their recognition process, but rather a combination of them, plus additional cues. For example, by taking first the choices of the character models from CG measurement for those models formed by simple bays and the M measurement for characters which contain an upper opening facing the west, and then the LA distance measurement for the remaining characters, we end up with 26 characters which have the same ranking as the human beings, i.e., 72.22%.

Table 4 The most legible and distinctive character models ranked by subjective experiment and distance measurements.

Legibility	AND	XOR	CA	LA	ENT	INF	MID1	MID2	M	CG
A1	A1	A1	A1	A1	A1	A2	A1	A1	A1	A1
B3	B3	B3	B3	B3	B3	B2	B3	B2	B2	B2
C1	C2	C2	C2	C2	C2	C2	C2	C2	C2	C1
D3	D1	D3	D1	D1	D1	D1	D1	D1	D1	D1
E2	E2	E3	E2	E2	E2	E2	E2	E2	E2	E2
F1	F2	F3	F2	F2	F2	F2	F2	F2	F2	F2
G3	G4	G5	G4	G4	G4	G4	G4	G4	G5	G5
H1	H1	H1	H1	H1	H1	H1	H1	H1	H1	H1
I1	I2	I1	I2	I2	I2	I2	I2	I2	I1	I1/I2
J1	J2	J2	J2	J2	J2	J1	J1	J1	J2	J1
K1	K1	K3	K1	K1	K1	K1	K1	K1	K3	K1
L1	L1	L1	L1	L1	L1	L1	L1	L1	L1	L1
M4	M4	M3	M4	M4	M4	M2	M2	M2	M3	M2
N1	N1	N1	N1	N1	N1	N1	N1	N1	N1	N1
O2	O1	O2	O1	O1	O1	O1	O1	O1	O2	O2
P1/P2	P1	P1	P1	P1	P1	P1	P1	P1	P1	P1
Q1	Q1	Q1	Q1	Q1	Q1	Q1	Q1	Q1	Q1	Q1
R2	R1	R1	R1	R1	R1	R1	R1	R1/R2	R1	R1
S2	S1	S3	S1	S1	S1	S1	S1	S1	S1	S1
T1	T1	T1	T1	T1	T1	T1	T1	T1	T1	T1
U2	U1	U2	U2	U2	U1	U1	U3	U3	U2	U3
V1	V1	V1	V1	V1	V1	V1	V1	V1	V1	V1
W2	W2	W1	W2	W2	W2	W4	W4	W4	W1	W4
X2	X1	X1	X1	X1	X1	X1	X1	X1	X1	X1
Y1	Y1	Y2	Y2	Y2	Y1	Y1	Y2	Y2	Y2	Y2
Z1	Z2	Z1	Z2	Z2	Z2	Z2	Z2	Z2	Z1	Z1/Z2
12	13	12	13	13	13	13	13	13	12	14
22	21	21	21	21	21	22	21	21	22	21
33	31	32	32	31	31	31	33	33	33	31
43	43	43	43	43	43	42	43	43	41	42
52	52	52	52	52	52	51	52	52	51	51
62	64	64	64	64	64	61	64	64	61	64
71	71	74	71	71	71	73	73	73	73	73
83	82	83	83	83	82	82	83	83	83	82
92	91	91	91	91	91	91	92	92	91	92
01	01	02	02	01	01	01	01	01	02	02

CONCLUDING REMARKS

The legibility and distinctiveness of various forms of handprinted characters have been investigated. Legibility is obtained from a subjective experiment using a tachistoscope and distinctiveness was measured by distance functions. While the distance measurements may produce characters which are more distinct in shapes, these characters may not be the same as those found most legible to humans; indicating that selective information theory fails to explain human form perception. Indeed, human recognition of characters is based on a long learning process, wide experience, and innate inheritance. However, given enough time and exposure to humans, there is a good chance that the most distinct set(s) of characters evaluated by distance measurements may eventually become the set(s) which would produce the maximum legibility. This may be seen from the results of some distance measurements, in particular the XOR operation which emphasizes shape differences among characters, e.g., models  which can be easily disambiguited from other characters which possess similar geometrical features, viz. 8, 0, 1, V, 2, I, U, O/D, 5, 5/8, and 1, for the above 11 models. These models would greatly facilitate recognition by computers equipped with visual peripherals such as optical scanners and image processors.

This paper forms a preliminary study of the integration of human recognition with quantitative measurements with the objective of producing a set or sets of characters for maximum legibility and greatest distinctiveness for best machine recognition. This type of research appears to be unique in this domain and no doubt more work such as in-depth studies of small subsets of character models and their distinctive features, would be needed to achieve the goal of efficient communication.

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ON THE USE AND LIMITATIONS OF AVERAGING HANDWRITING SIGNALS

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Arnold J.W.M. Thomassen

INTRODUCTION

Ensemble averaging is a technique, used in many conditions where the reliability of measurement of a single sample record is reduced by some degree of noise. The measurement X_k may be assumed to be composed of a signal S_k and a noise component e_k:

$$X_k = S_k + e_k \tag{1}$$

where e_k is a stationary random signal and S_k is a fixed-duration transient with deterministic properties. The averaged signal M_k is obtained by:

$$M_k = \frac{1}{N} \sum_{i=1}^{N} (S_{ki} + e_{ki}) \tag{2}$$
$$= S_k + \bar{e}_k$$

If the noise in the given samples is uncorrelated and the mean value of the noise is zero, then for large N:

$$M_k = S_k \tag{3}$$

Averaging of N sample records thus results in noise reduction: the variance of the error component of a single value k in M_k will be reduced with a factor 1/N (Bendat and Piersol, 1971; Regan, 1972). Apart from the random error, there may be a bias in each measurement, for instance caused by non-stationarities of the signal transient such as increasing or decreasing mean square value in the series of individual sample records. The main advantage of ensemble averaging over other methods of noise reduction such as low-pass filtering is that ensemble averaging selectively cancels noise contributions without affecting the 'true' signal portion of the spectral characteristics of the signal.

One major assumption in using averaging is the notion of time-lock. In many applications, the time reference used is an external event that triggers the occurrence of the transient to be measured. Furthermore, transients are assumed to have fixed duration. In practice, some jitter in the transient onset time and some variation in duration are taken for granted if they fall within predetermined limits. In handwriting signals, however, as well as in other types of free-floating human motor output, there are no external time-reference points and duration of segments having identical spatial representation may vary substantially. Nevertheless, it would be very useful in analysis, pattern matching and simulation of handwriting if an average representation of a specific stroke, letter or word produced by a certain writer were available to represent the idealized shape and dynamics of such handwriting segments for that person. Therefore, we shall take a look into the main problems in selecting adequate time-reference points and in dealing with duration variability.

Selecting the Time-Reference Points

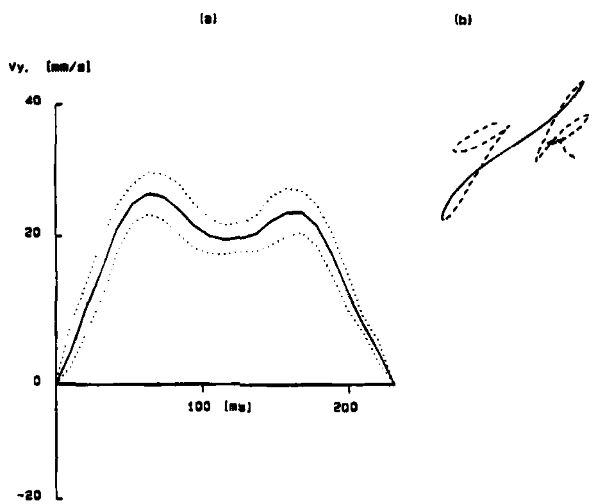
Before averaging of handwriting can take place, time-reference points have to be selected. From studies of handwriting it is known that the handwriting signal can be segmented reliably by taking the part of the displacement signal between two zero crossings in the Y-velocity signal as a stroke (Teulings & Thomassen, 1979). Another solution, taking the moment of maximum Y velocity as time reference is rejected because of its greater dependence on the velocity profile. Y strokes defined in the former way have the property of reflecting a combined agonist-antagonist muscle group action. Theoretically, the use of the acceleration signal would thus introduce the possibility of separating agonist and antagonist action. In practice, however, the double differentiation of the displacement signal leads to an unacceptable increase in noise level. The basic unit in averaging, therefore, will be a stroke in the velocity domain, the time-reference points being two adjacent zero crossings in the Y velocity. This also determines the time segment of the X velocity belonging to the same stroke. The velocity profile of a Y strokes of a specific class (e.g., "last downstroke in a") is very reproducible within a subject and varies from triangular to sine shaped. Velocity profiles of strokes that occur in a transition from clockwise to counterclockwise movement are often bimodal or broadened, but their shape is reproducible for a given class (e.g., the connecting stroke from g to e). According to the criteria by Bendat and Piersol (1971) we should classify single strokes as being deterministic transients (Note 1). Combined with the knowledge that zero crossings in the Y velocity are reliable time-reference points this justifies the use of averaging handwriting signals of a single subject at the local (i.e., stroke) level. It should be noted that, although single strokes can be considered to be deterministic, large segments of handwriting contain such a large amount of time and amplitude variations that they have to be classified as random time series. As a consequence, methods used for random data analysis like spectral analysis are still applicable on larger segments (minimally lasting five seconds) (cf. Maarse, Schomaker and Thomassen, 1985).

Duration Variability

When a subject is asked to write a page of text, the movement duration of a specific letter will vary among the different realizations of that letter due to non-intended size and context effects. Thus, after selecting time-reference points, we shall have to normalize the time axis of the different replications before averaging. A comparable problem is encountered in speech recognition where the duration of the phonemes within a word may vary across several replications of the same word. If a minimum of assumptions with respect to signal shape is preferred and a fast computer is available, normalization of time axis can be done by means of Fourier transform (Note 2). A forward Fourier transform is done to obtain the amplitude and phase frequency spectrum, followed by an inverse Fourier transform with a time spacing of samples as determined by the ratio of old duration and normalized duration.

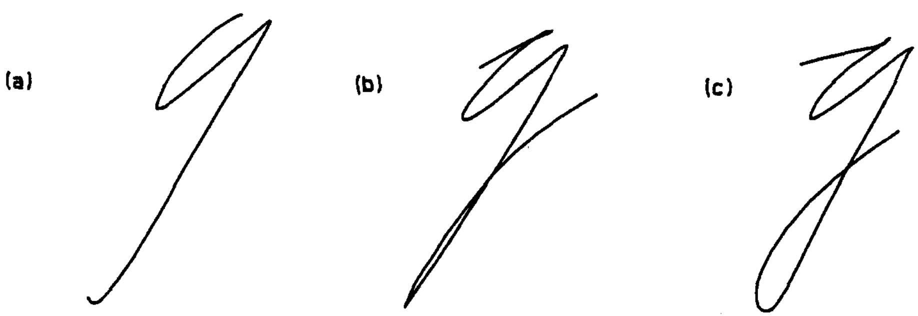
At the *stroke* level, an averaging technique may provide a reliable estimate of the strategy used to produce the displacement in that stroke. The velocity profile of a stroke determines the efficiency of its movement (Teulings, Thomassen & Van Galen, 1985). Figure 1 shows the typical (averaged) Y-velocity profile of a large up stroke in which a change of sense of rotation is produced. The stroke is the basic averaging unit. After time-axis normalization, the only sources of variability in a set of strokes are the stroke-size differences and differences in the shape of the velocity profile. Strokes may have equal size (area of the velocity profile) and have different shape of velocity profile.

Figure 1 a. Average Y-velocity profile of a single stroke (g-k), 8 replications (drawn line is average, dotted lines are average plus and minus standard deviation). b. Spatial representation of the stroke in Figure 1a. (drawn line) and its context (dashed).



Knowing that single strokes can be averaged, it would be interesting to know to what extent a given record of handwriting can be averaged. It is hypothesized that if the right time-reference points are chosen, sequences of strokes can be averaged also reliably if the movements are overlearned, e.g., in the case of a single *letter*, written by an experienced writer. The problem in averaging multiple-stroke handwriting segments is that each further stroke introduces a time variability, apart from the already mentioned size and shape variability. If the movements are overlearned, a handwriting segment can be assumed to be homothetic, i.e., ratios of stroke durations are constant in different realizations (Viviani & Terzuolo, 1980). Figure 2 shows the effect of the location of time reference for one letter. In 2a, it may be seen that the choice of Y-velocity maxima in connecting strokes leads to an unacceptable distortion of the average letter representation in the spatial domain. Cause of the distortion is the fact that connecting strokes are embedded in the motor context of the end of the previous letter and the start of the next letter. A better choice may be seen in 2b, where the first and last zero crossings of the Y-velocity signal within the letter proper were used as time-reference points, disregarding the connecting strokes.

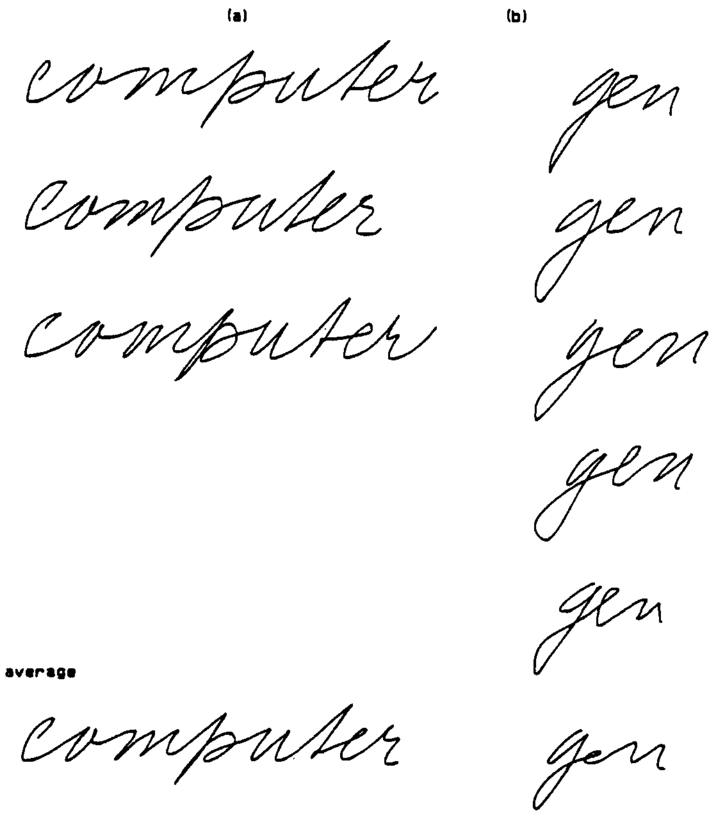
Figure 2 a. Average g, zero crossings in Y velocity used as time references, 6 replications connecting strokes as time references, 6 replications. b. Distorted average g by using peak Y velocity in connecting strokes as time references, 6 replications. c. Typical single g for this subject.



In the case of naturally produced handwriting, the straightforward averaging of even larger units, such as *words*, is made increasingly more difficult by hesitations, pen-up movements and allograph variations that may be expected to disturb the homothetic features of the movement sequence. Also, in these larger units, there is an increased probability of non-overlearned sequences to introduce a greater time variability. For instance, connecting strokes may or may not be part of a motor program, depending on the degree of automation of the specific sequence of letters. In sequences encompassing instances of evidently large time variability due to occasional hesitations or pen-up movements, a time warping technique might be necessary, i.e., segmenting the handwriting into pieces each of which can be assumed to be homothetic, and normalizing time for each segment separately. Once this has been done, ensemble averaging or pattern matching can be applied. In speech recognition, this problem is solved, using an optimal time-alignment procedure called dynamic time warping (Brown & Rabiner, 1982).

From an exceptionally regularly writing subject the average word computer could be obtained (Figure 3a), but hesitations and prolonged stroke duration may cause distortions (Figure 3b) if they are not accounted for in the averaging procedure. The average word gen is distorted by a hesitation before executing the down stroke in g in the last of the five replications (the hesitation cannot be inferred from the spatial representation). In order to assess the discussed problems encountered in averaging multi-letter segments of handwriting in greater detail, we shall analyze some experimental data in the next sections of the present paper, using time-normalization and averaging techniques. The following aspects will be illustrated.

Figure 3 a. Three different replications of the word computer and the average word. b. Five different replications of the word gen and average word, distorted by hesitation.



Deviation from the Average Handwriting Pattern

Deviations from the average Y-velocity pattern can be attributed to time, size and shape variations (note that in the current study stroke size is not normalized in any way). Possibly large deviations from the average pattern are indicative of transitions between discrete states in the motor production process. Such transitions are likely to occur during movements connecting one letter to the next. Consequently, three types of connecting strokes will be examined.

Variability of Zero-Crossing Times

If we know the average stroke duration of each stroke, the uncertainty of finding the stroke ending of the n-th stroke in some time segment in the velocity signal increases with the number of strokes since each new stroke adds its variability in duration. Normalizing the time axis will have the effect of reducing this uncertainty in a curvilinear fashion, maximum uncertainty remaining around the middle of the handwriting time segment. In the limiting case where the variance of stroke duration is the same for all strokes, the variance of stroke onset time will be proportional to stroke number (first stroke is number zero) before normalization. After normalizing the time axis, the variance of stroke onset time will be proportional to $n * (N - n)$, where n is the stroke number and N is total number of strokes.

METHOD

Subjects

Two adult right-handed male subjects, aged 49 and 28, participated in the experiment.

Materials

The movements of the tip of the writing stylus were recorded by means of a large-size writing tablet (Calcomp 9000) connected to a computer (PDP 11/45). The laboratory-made writing stylus was equipped with a pressure transducer. The stylus contained a normal ball-point refill. Thirty-eight pseudowords were printed on specially prepared A4 response sheets in twelve rows of two to five words each. A row contained a certain 'family' of pseudowords allowing specific comparisons. The rows themselves were placed in a quasi-random order. Pseudowords contained minimally three letters, the maximum was five letters. From this material, the pseudowords ague, agne and agee are selected for the present purpose since they contain an identical part (ag) and a contrasting part, that starts with three possible types of large connecting strokes, i.e., g-u which ends in a sharp cusp, g-n which ends in clockwise turn, and g-e which consists of a clockwise and a counter-clockwise turn in one stroke.

Procedure

The subjects' task was to write on the response sheet immediately below the place where the pseudowords were printed. The response sheet was placed on the writing tablet and was held by the subject in a convenient position and at a preferred angle, just as in a normal writing situation. A pseudoword had to be written fluently without raising the pen. A session consisted of writing the 38 pseudowords on the sheet once. An experimenter-controlled tone sounded to signal the onset of a 2.5 s. period during which the writing could be produced. Two tones signalled the end of the interval. All pseudowords could easily be written within this 2.5 s. period, so that no time pressure was imposed on the subject. The experimenter took care that he did not start the interval until the subject's hand rested at approximately the appropriate position for the next word. If the subject was not satisfied, due to hesitations, errors (e.g., selection of incorrect allographs), jerks, late starts or slow movements, he was immediately given another trial in which the word was written below the rejected product. A session, which lasted only four minutes, could be followed by a further session after a rest of a few minutes, or sessions could be separated by a whole day. Each subject completed ten sessions.

Signal Processing

The X and Y-coordinate values and the pressure at the tip of the pen (Z coordinate) were sampled during 2.5 s. intervals at a 105 Hz rate, samples having an accuracy of 0.02 mm. in both X and Y directions. Prior to our analyses, these handwriting data were digitally filtered with a finite-impulse response filter (pass band 0 to 10 Hz, transition band 10 to 30 Hz; Rabiner & Gold, 1975). Since the orientation of the handwriting was left to the writer's preference data were automatically rotated to obtain a horizontal baseline, using the low extremes of small letters as a reference. Velocity signals were calculated by differentiating the handwriting coordinates versus time using a five-point finite-differences impulse response (Dooijes, 1984). Handwriting was segmented on the basis of zero crossings in the Y-velocity signal, the first point in a segment being the start of the first down stroke in the first letter (a), the last point being the end of the last stroke of the last letter (e) in the analyzed pseudowords. Of each word (ague, agne and agee) eight replications per subject were entered in the analysis.

The average duration of each word was used as the reference duration in the time-axis normalization. After time normalization, the average Y-velocity pattern and its standard deviation (SD) pattern were calculated (N=8) for each word and each subject separately. For comparison purposes and data reduction, the following measures were calculated per Y stroke. From the time-normalized replications, SD of stroke size and SD of stroke duration were determined. From the average Y-velocity and the individual time-normalized Y-velocity replications, the SD of the average Y-velocity pattern was calculated. The latter measure was obtained by pooling sums of squared deviations per stroke.

RESULTS

The mean word durations are shown in Table 1. Of the ten sessions, two sessions were lost due to technical problems.

Table 1 Average durations per word, Subject 1 and 2.

	Subject 1				Subject 2			
	[ms]	SD	[samples]	N	[ms]	SD	[samples]	N
ague	1467	(68)	154	8	1457	(100)	153	8
agne	1419	(52)	149	8	1423	(80)	150	8
agee	1305	(41)	137	8	1257	(102)	132	8

Figure 4 shows the average handwriting pattern and the Y-velocity profiles for the three pseudowords written by Subject 1. Notice the broadened SD at the large down stroke in g which occurs in all words, but which is maximal in ague. In this word, the shape of the average Y-velocity minus SD is irregular at the the large down stroke in g. The Y-velocity profile in agee shows the typical shape of the g-e stroke (stroke number 8). Of all three patterns, the agee pattern is the most stable, especially at the two es.

Figure 4 Average handwriting and Y-velocity profile for the three pseudowords ague, agne and agee, (Subject 1). Dashed lines are average plus SD and average minus SD. There were 8 replications per word.

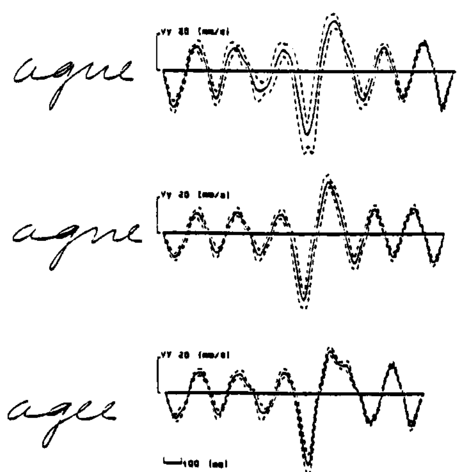
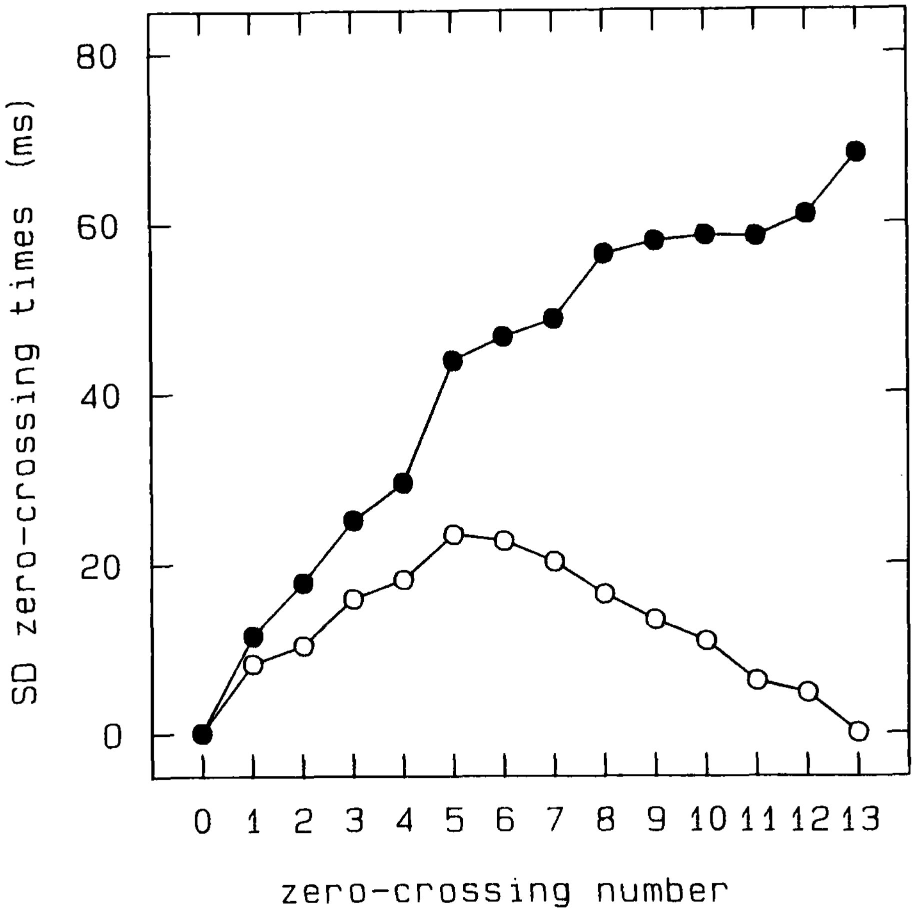


Figure 5 shows the variability in time of zero crossing, before and after time-axis normalization. Note the overall decrease in variability and the curvilinear relationship between stroke number and stroke-onset time variability after normalization.

Figure 5 Standard deviation of Y-stroke onset times in the pseudoword ague, before (closed circles) and after (open circles) normalization of time axis (Subject 1) N=8.



Figures 6, 7 and 8 allow a comparison of three types of variability per stroke. The *a panels* show the deviation from the average Y-velocity pattern. At the seventh stroke, which is the large down stroke in g, there is a peak in the variability of the Y-velocity. This peak is not related to the curvilinear stroke-onset variability caused by time normalization, because it occurs in the same place for the 13-stroke words ague and agne as for the 11-stroke word agee. Shifting the first time-reference point up to three strokes to the right, moreover, had no influence on this effect: variability always remained maximal at the large downstroke in g (not shown). The largest variability (peak as well as overall) is reached in ague, followed by agne, and finally agee if both subjects are combined. The *b panels* show stroke size variability. There is no clear peak at the seventh stroke. In fact, a peak occurs at the eighth stroke which is the connecting stroke g-*. Only in Figure 8 (agee) stroke size variability is also high at the seventh stroke as written by Subject 1. The *c panels* show stroke-duration variability which is increased at or around connecting strokes (numbers 4, 8, 12). There is no clear relationship between duration variability and the variability in Y-velocity at the seventh stroke itself.

Figure 6 Standard deviation of Y velocity from average pattern per stroke (a), standard deviation of stroke size (b), and standard deviation of stroke duration (c) in the pseudoword ague (Subject 1, circles; Subject 2, squares), N=8.

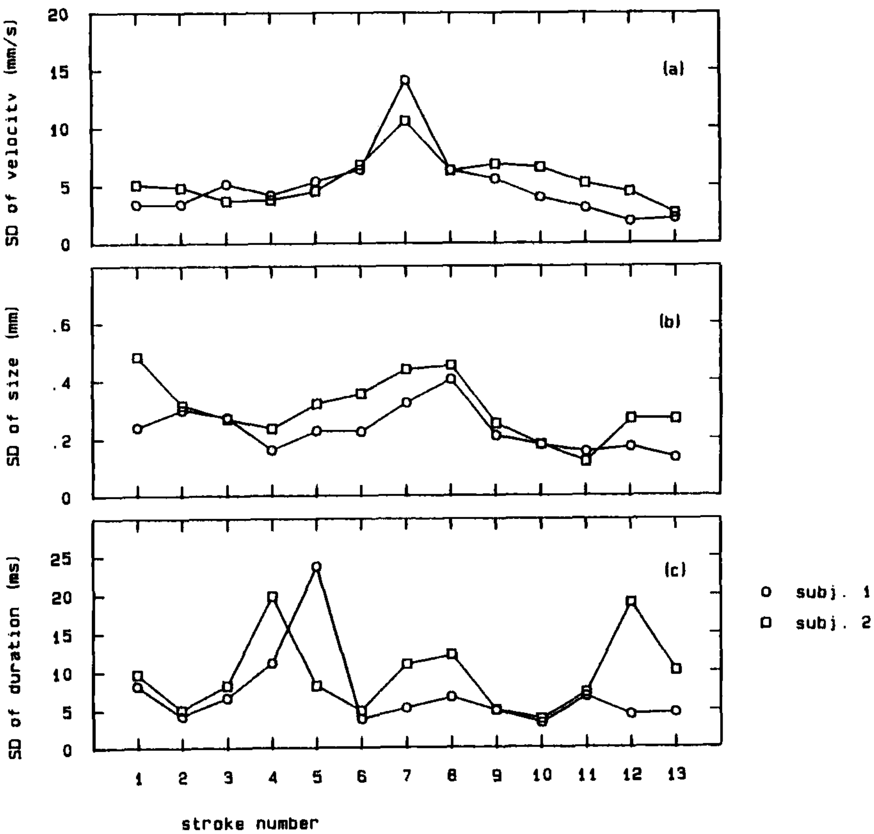
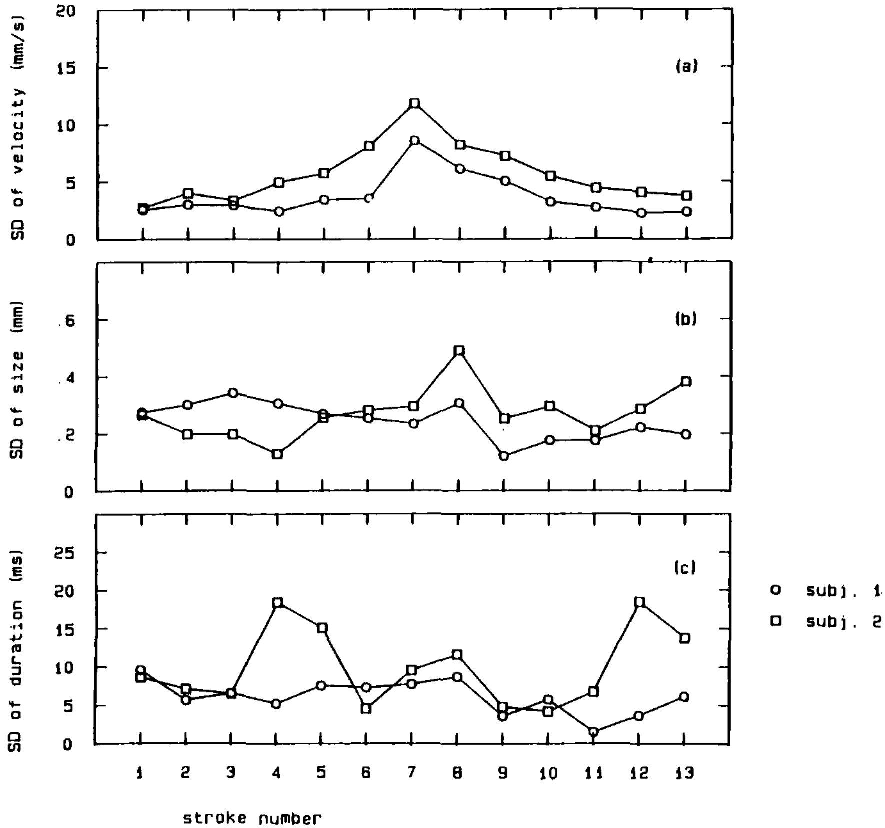


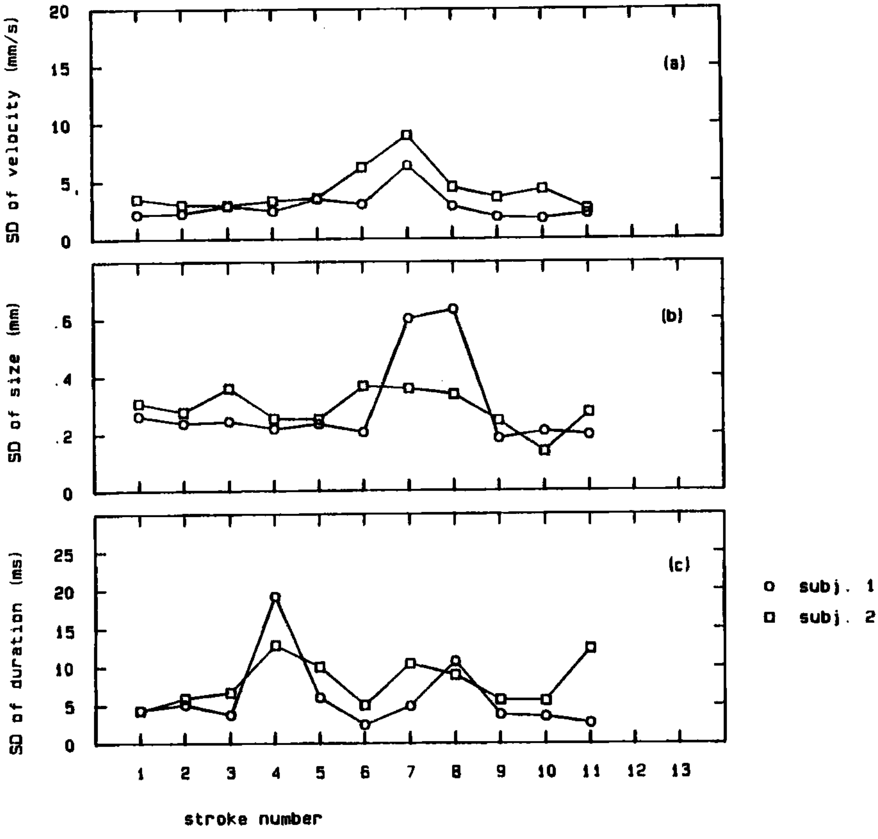
Figure 7 Standard deviation of Y velocity from average pattern per stroke (a), standard deviation of stroke size (b), and standard deviation of stroke duration (c) in the pseudoword agne (Subject 1, circles; Subject 2, squares). N=8.



DISCUSSION

An interesting finding of the present study is that handwriting segments up to four-letters can be averaged very well because the consistency across the individual replications is high, even though the task involved pseudowords. Normalization of the time axis was a sufficient condition to obtain a reliable average. Within a subject, normalizing stroke size seems to be unnecessary. The detected peak deviation in the Y-velocity remains a problem to be explained. The possibility of an artefact caused by the normalization operation may be excluded since the effect was independent of number of strokes or time reference chosen. Size and duration variability of the stroke itself are unlikely to cause the effect (Figures 6, 7 and 8). Another source of error could be variable shape of the velocity profile of the large down stroke in g. Inspection of Y-velocity profiles of the individual

Figure 8 Standard deviation of Y velocity from average pattern per stroke (a), standard deviation of stroke size (b), and standard deviation of stroke duration (c) in the pseudoword agee (Subject 1, circles; Subject 2, squares), N=8.



replications indicated that this was not the case. In fact, the source of the effect can be traced back to the occurrence of duration variability earlier in the pattern, at the fourth and fifth stroke. Possibly this variability can be explained by anticipation of the large down stroke in g and the subsequent large connecting stroke. In this case, the duration variability did not cause visible distortion in the spatial representation of the average. It is advisable, however, to analyze the variability of stroke onset times (Figure 5, closed circles) before time-axis normalization. At the location of sudden increases in variability the handwriting signal should be split up in subsegments. To obtain a more reliable estimate in the case of the pseudoword ague), subsegments would be: (a) strokes 1 to 4; (b) stroke 5; and (c) strokes 6 to 13.

The time normalization technique can be a valuable tool in movement analysis, pattern matching and simulation. Before it can be applied, however, careful inspection of the stroke-onset time variability appears to be needed. When the homothetic assumptions are violated in a handwriting segment, subsegments have to be defined, thereby 'warping' the time axis. In movement analysis, time normalization and averaging can be used to detect special strategies in the velocity profiles that are used by the subject to obtain specific curvature shape in the spatial domain. In pattern matching of handwriting signals the technique can be of use by providing reliable averages that are used as templates. In the matching process itself, time normalization is used to enable matching of a specific handwriting pattern with the template. In simulation of handwriting, time-axis normalization is used to obtain reliable averages of letters and connecting strokes from a writer. Only reliable averages allow the determination of important parameters in the simulation model.

Use of the Fourier transform has the disadvantage of being time consuming. Fast Fourier has the disadvantage of requiring sample record sizes that are powers of two (the technique of adding zeros appeared to cause unacceptable distortion). The use of splines is rejected because it also can introduce serious estimation errors. During the last few years, much work has been done on this subject. Methods of interpolation using finite impulse response differentiation are promising with respect to calculation time (Sudhakar, Agarwal & Suhash, 1982).

FOOTNOTES

1. If an experiment producing specific data can be repeated many times with identical results, within the limits of experimental error, then the data can be considered deterministic. If such an experiment cannot be designed, then the data are considered random (Bendat & Piersol, 1971).
2. The steps necessary to achieve time-axis normalization using Fourier transform are as follows: (1) Determine normalized duration Tn and normalized number of samples Nn by averaging movement duration of the different replication; (2) Calculate x and y velocities. For x and y: repeat steps 3. to 7. for each sample record with N_i values; (3) Make sample record circular by linear detrending; (4) Apply forward Fourier transform with N_i frequency domain estimators, with k=0 to N_i-1.

$$X_k = \sum_{n=0}^{N_i-1} x_{n\,e} \, [-j\,\pi\, kn/N_i] \qquad (4)$$

(5) Apply inverse Fourier transform with N_n time domain estimators, with n=0 to N_n-1.

$$x'_n = \sum_{k=0}^{N_i-1} X_{k\,e} \, [+j\,\pi\, nk/N_n] \qquad (5)$$

(6) Decircularize sample record by restoring linear trend;
(7) Gain correction (multiply sample record with N_i/N_n).

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Overview

The papers in this Section were mostly concerned with different aspects of the motor programme. These were considered in the wider context of memory processes, and the interaction of motor memory with memory of other modes of behaviour sheds light on the nature of the motor programme. If handwriting performance was to be shown governed by the same kinds of effects of context and sequential chains, it might serve the function of integrative understanding of human behaviours. The first contribution by Nihei investigated the relation between phonetic memory and motor memory by asking subjects to perform rapidly repeated writing while vocalizing different sounds. Different amounts of slips of the pen were produced depending on whether the vocalized sounds were related to the pronunciation of the repeatedly written character. However, similar patterns of the results were found whether the subjects were writing kana or kanji characters in the Japanese language. It has been generally agreed that the relation between sound and script for kana and for kanji are different, and it may be worthwhile to look into the similarity of the results for the two scripts, in clarifying the relationship between motor and phonetic memories. Also, the rapidly repeated writing paradigm is somewhat reminescent of the semantic satiation paradigm (cf., L.A. Jakobovits and W.E. Lambert. Semantic satiation among bilinguals. *Journal of Experimental Psychology*, 1961, 62, 576-582.) in which the repeated pronunciation of sounds of words resulted in attenuation of their meanings. It may be possible that some similar mechanisms are responsible for the phenomena in the motor and auditory modes.

Thomassen and Schomaker asked their two subjects to write the letters *e* and *l* and compared between-letter context effects in terms of preceding and succeeding letters, both in terms of stroke duration and size. Contextual effects were found, and those of preceding letters were stronger than succeeding letters. Where motor sequences were not organized on a discrete basis but in terms of simultaneous activation of different muscle groups for the sequential motor performance, there were clear indications of co-articulation. In this respect, letter writing was similar to vocalization. The common motivation was the relatively slow onset and offset times for individual articulations, whether they were to produce sounds or writing movements. Again, this study suggested commonalities in the oral and written production of language, and context effects for writing were found to be similar to speech.

The study by Chau, Kao, and Shek made use of the opportunity provided by the unique configuration of a category of Chinese characters to examine the issue of the nature of the stored motor programme for word sub-components. These Chinese characters were each composed of two constituent characters which can exist on their own in other contexts. Execution times for such composite characters were compared with those of their components written separately. Further manipulations involved inserting other motor as well as cognitive tasks in between the execution of each pair of components. Indications supported a hierarchical, multi-level model of processing, with parallel preparation for succeeding strokes being made together with the execution of preceding strokes. Also, in terms of stroke duration, there was a clearer effect of preceding strokes on succeeding strokes. This effect was similarly found in the preceding paper by Thomassen and Schomaker.

The next study attempted to relate different modes of handwriting control to models of handwriting. Shek, Kao, and Chau looked at the allocation of attentional resources, while subjects were asked to perform a tracing and a copying task. This primary task, with characters of different frequencies of usage and complexity, was paired with a seconary task of reaction time responses with the foot. There was no difference in reaction time performance for tracing and copying. But there was some indication that attentional arousal was higher during tracing; and, the discrepancy found between pressure and reaction time data suggested that the nature of resource allocation in tracing and copying might be different, with more resources being distributed to motor initiation and execution processes under tracing. Tracing characters of low complexity was associated with higher writing pressure.

Specifically comparing spatial and temporal structures, the paper by Teulings, Thomassen and van Galen researched for the invariance of motor programmes. Applying the method to various realizations of a complex handwriting pattern, the method uses three criteria: signal-to-noise ratio, inter-characteristic correlations, and inter-condition correlations. This paper presented a method to decide which of the two structures was the least variant. The results consistently showed that spatial structure was more invariant than temporal structure. It was pointed out that apparent findings of invariant temporal characteristics in handwriting movements may be due to the motor system producing the smoothest trace to satisfy the desired spatial outcome; and, effectively temporal invariance was derived from spatial invariance.

Graphonomics: Contemporary Research in Handwriting
H.S.R. Kao, G.P. van Galen, R. Hoosain (eds.)

DISSOCIATION OF MOTOR MEMORY FROM PHONETIC MEMORY: ITS EFFECTS ON SLIPS OF THE PEN

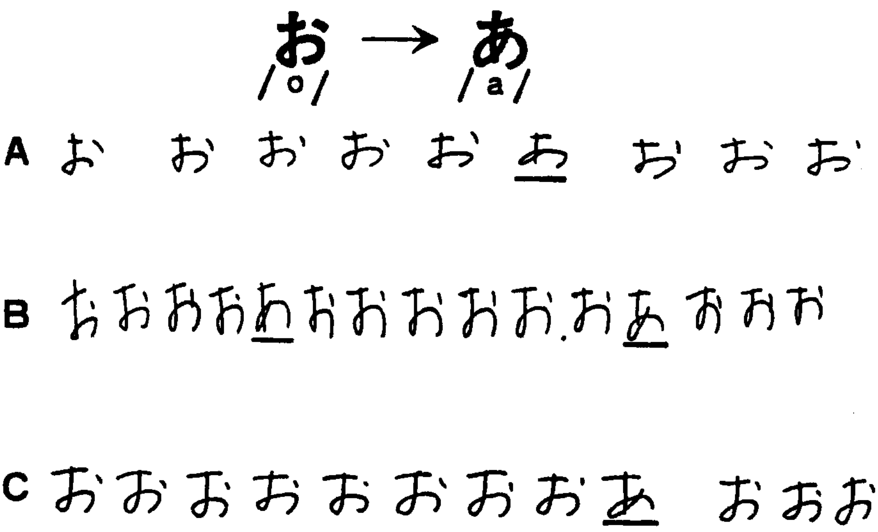
Yoshiaki Nihei

INTRODUCTION

The act of handwriting is considered to be performed by activating and triggering motor memories for characters. The most common way of activating the motor memories would be through activating their phonetic memories, or sometimes through activating the visual memories (Luria, 1966). In the act of handwriting, motor memories and phonetic memories for characters are closely associated with each other. The so-called "Schreibendes Lesen" in some aphasic patients would reflect the close relationship between the motor and phonetic memories (Iwata, 1976). However, it is not easy to dissociate the two types of memorial representations, and to clarify their relationship, because of their close connection.

In Nihei (1984)[1] a simple experimental method was proposed which taps the linkage among motor memories for writing characters. This method was called "rapidly repeated writing (RRW)." In RRW, subjects are asked to write a designated character repeatedly as quickly as possible. After a number of repetitions, some proportion of the Ss (the proportion differs from character to character) start to make slips of the pen writing unintentional characters instead of the designated one (Figure 1). As shown by the examples in Figure 1, the unintentional character appearing as a slip shares common movements in handwriting with the intended character. The earlier study showed that in order for the slip in RRW to occur, there had to be similarity in the sequence of movements, not just in the appearance of the characters. These suggest the presence of a link between the motor memories of the two characters that share common movements with each other. The following process was supposed to explain the occurrence of slips of the pen in RRW: (1) By repeated use of the motor memory for a designated character, activation of the memory spreads over other memories which link with that of the intended character; (2) When the frequency of usage for a simultaneously activated memory is higher than for the intended one, the former tends to be triggered, and then slips of the pen occur; (3) Slips caused by RRW are conceived of as capture errors according to the categorization of slips by Norman (1981).

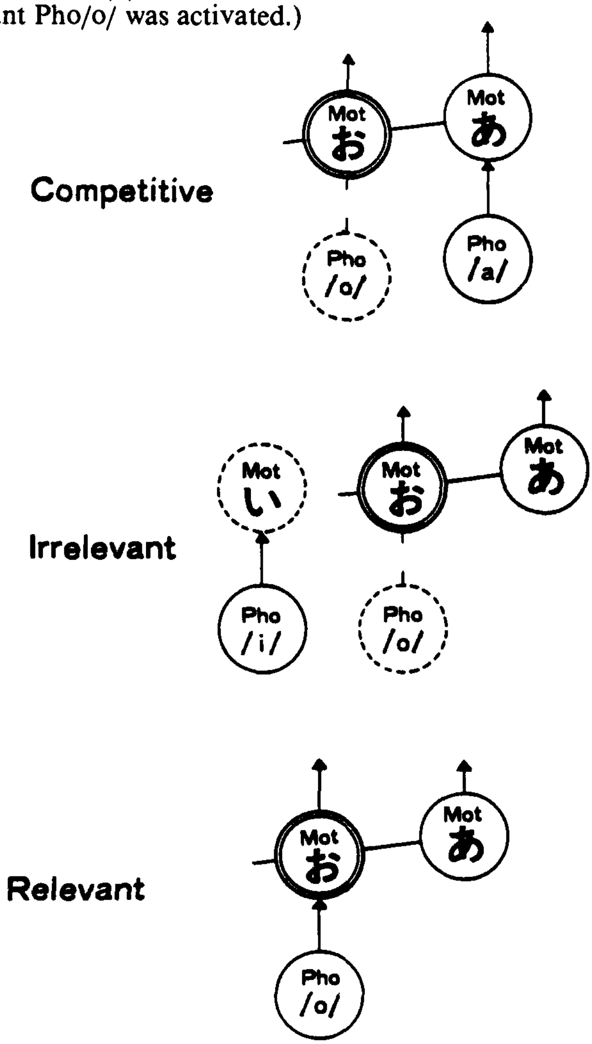
Figure 1 Examples of slips of the pen in RRW of Hiragana /o/ (Subjects (A-C) wrote Hiragana /a/ unintentionally after repeated writing of /o/. Note that the character appearing as slips shares common movements in handwriting with the intended character.)



Using this technique, we may be able to investigate the linkage between the motor and the phonetic memory of characters. If it is important for handwriting that the motor memories are activated and reinforced by the activation of the corresponding phonetic memories, we may expect some changes in handwriting behavior to occur as a result of a dissociation of the two forms of memories or an inhibition of the activation of the phonetic memories. In fact, an investigation has shown that the number of mistakes during writing was increased manyfold when normal children in the initial stages of education were instructed to write with their mouths open (Nazarova, 1952 cited in Luria, 1966).

The present investigation intends to investigate how the dissociation between the motor memory and the phonetic memory of a character influences slips of the pen in RRW. There were three experimental conditions of activating the phonetic memories (Figure 2): (1) Activating the phonetic

Figure 2 Schematic description of the supposed mechanisms involved in the three experimental conditions.
(Mot (Motor Memory), Pho (Phonetic Memory). Arrows denote activation. Ss performed RRW of the character /o/ in all three conditions. Activation of Mot/o/ spreads over Mot/a/. In the Competitive condition, Pho/a/ was activated by covertly articulating /a/ while writing the character /o/. In the Irrelevant condition, Pho/i/ was activated. In the Relevant condition, the relevant Pho/o/ was activated.)



memory of another character than that which is to be written in RRW, specifically of a character the motor memory of which may be assumed to have features in common with that of the intended character (Competitive condition); (2) Activating the phonetic memory of another character than that which is to be written in RRW, specifically of a character the motor memory of which may be assumed to have no features in common with that of the intended character (Irrelevant condition); (3) Activating the relevant phonetic memory of the character which is to be written in RRW (Relevant condition). In conditions (1) and (2), the motor and the phonetic memory for a character are necessarily dissociated in writing. In condition (1), moreover, the activated competing motor memory receives activation also from the corresponding phonetic memory, so that it will most easily triggered. As a result, the most frequent slips of the pen should be expected in this condition. In condition (2), the relevant phonetic memory is inhibited by the irrelevant phonetic memory. Some extent of increase in slips of the pen should be expected in this condition.

EXPERIMENT 1

Method

Material

Hiragana (Japanese phonogram) /o/ (see Figure 1) was selected as the material of RRW for the following reasons: (1) A preliminary RRW experiment with /o/ indicated that RRW of it caused slips of the pen in a fair proportion of the subjects; (2) The most frequent character appearing as slips was /a/ which belongs to the same categories, Hiragana and vowel, as /o/. The character /a/ and /o/ share common and similar movements in handwriting. The frequency of usage of /a/ is about three times that of /o/ (Hayashi, 1982).

Subjects

In total 114 undergraduates served as subjects. They were exclusively right-handed.

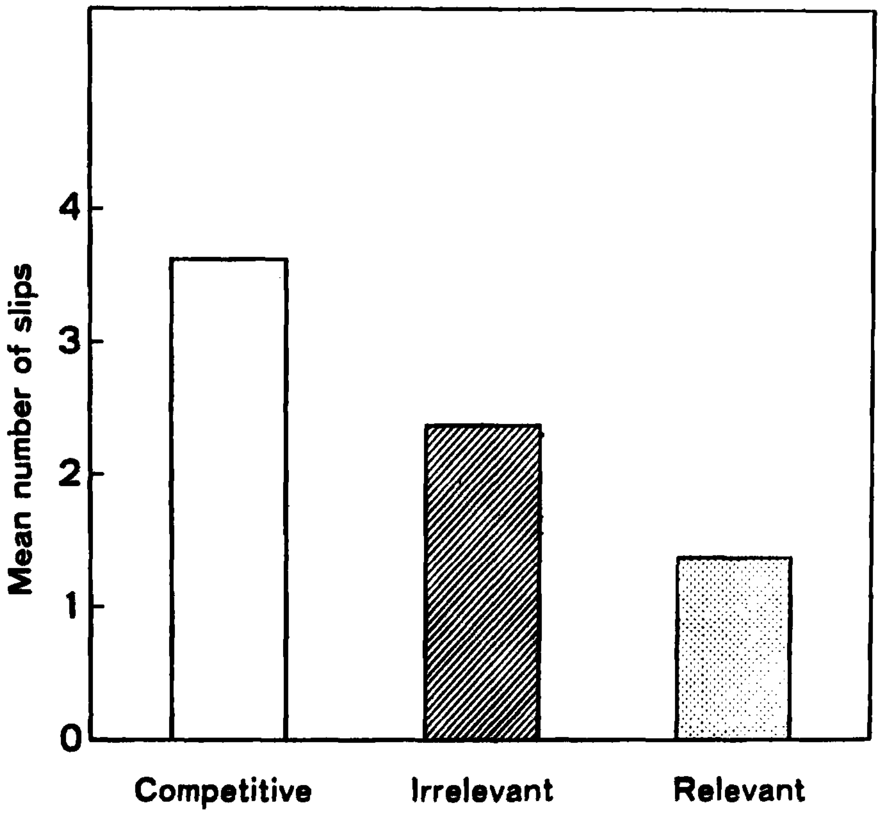
Procedure

Subjects in three groups performed RRW of /o/. They wrote the designated character /o/ repeatedly as quickly as they could with a pencil on B4 paper for two minutes. The activation of the phonetic memory in each condition was attained by the covert articulation of a character name every time a character was written. Each phonetic condition was as follows (see Figure 2): (1) Competitive condition: Ss were instructed to write /o/ rapidly and repeatedly, articulating /a, a, a.../ covertly. The character /a/ had appeared as the most frequent slip in a preliminary RRW of /o/. Thus it can be supposed that the motor memory for /o/ has a close link with that for /a/, a fact that can also be inferred from the common strokes in the character /a/ and /o/. Under this condition, the motor memory for /o/ is expected to compete with the simultaneously activated motor memory for /a/ which may be reinforced by the activation of corresponding phonetic memory /a/; (2) Irrelvant condition: Ss performed RRW of /o/ articulating /i, i, i.../ covertly. The character /i/ had not appeared as slips at all in the preliminary RRW experiment of /o/. So it can be supposed that the motor memory for /o/ has no linkage with that of /i/, and that the irrelevant motor memory /i/ does not compete with that of /o/ so actively; (3) Relevant condition: Ss were asked to write /o/ rapidly and repeatedly, covertly articulating the relevant character name /o, o, o.../. All Ss were asked not to correct or add any strokes when they noticed that they had made any error but to continue writing.

Results and Discussion

Slips made by Ss up to the 50th repetition were analyzed. The most frequent character appearing as a slip instead of /o/ was the character /a/ in all three conditions. The /a/ character amounted to 87.3% of the slips across the three conditions. Other characters appearing as slips were Hiragana /su/, /ka/, /mu/, /mi/, /i/, /tsu/, and /na/. All the characters, except for /i/, share common or similar movements with /o/. Slips which Ss could not explain what character they had written were also taken into account. However each of other Hiragana than /a/ amounted to less than three percent of all the slips. These results support the hypothesis that the activation of linked motor memories will result in slips of the pen in RRW favoring the production of more frequent characters. Figure 3 shows the mean number of slips made by the 50th repetition. The mean number of slips was 3.6 (SD 3.1) for the Competitive condition (N=40), 2.4 (SD 3.2) for the Irrelevant condition (N=37), and 1.4 (SD 2.4) for the Relevant condition (N=37). An analysis of variance on the number showed the significant effect of the phonetic condition ($F(2,111)=5.6$, $p<.01$). Slips occurred most frequently in the Competitive condition. By Tukey tests, the mean number of slips in the Competitive condition appeared to be significantly larger than in the Relevant condition ($p<.01$). No other differences reached significance. Similar trends were found as to the percentage of the subjects who had made any slip by the 50th repetition (87.5% for the Competitive, 62.2% for the Irrelevant, 54.1% for the Relevant condition, Chi-square (2)=10.9, $p<.01$). When the analysis was based on only /a/ slips, the significant effect of the phonetic condition was found again. The mean number of slips was 2.9 for the Competitive condition, 1.4 for the Irrelevant condition, and 1.1 for the Relevant condition ($F(2,111)=5.6$, $p<.01$). The rapidity of RRW (the total number of characters written in two minutes) did not differ significantly among the conditions.

Figure 3 Mean number of slips in each phonetic condition (Experiment 1).



Reinforcing the activation of the motor memory for /a/, which was activated in RRW of /o/, by activating the phonetic memory for /a/ increased the slips. In fact, the proportion of slips in writing /a/ was highest in this condition. Though the slips in the Irrelevant condition were more frequent than in the Relevant condition, the difference did not reach significance. Moreover, the slips which produced the writing of /i/ were quite rare (three out of 87 slips in this condition). Thus simply a dissociation between the motor memory and the phonetic memory for a character might have only a weak effect on errors, especially among adults.

The above results were obtained from an RRW experiment with simple characters. The next experiment was conducted to see if the results could be generalized to a situation involving more complex characters.

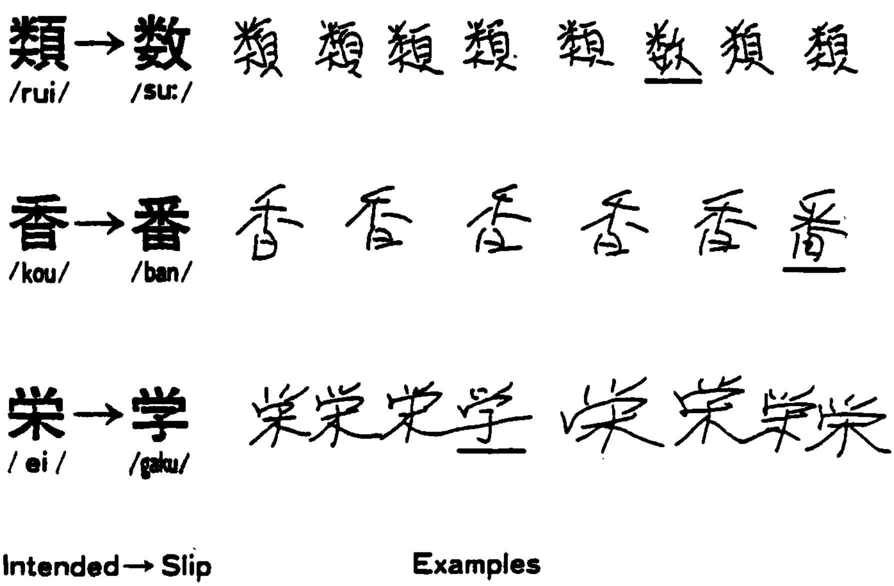
EXPERIMENT 2

Method

Material

Three Kanji (Chinese-originated characters) were used as the materials for RRW in the experiment. The characters, /rui/, /kou/, and /ei/, were known to cause slips of the pen in fair proportions of subjects from a preliminary experiment (Figure 4).

Figure 4 Examples of slips in RRW of Kanji /rui/, /kou/, and /gaku/. (Each example is the most frequent character to appear as a slip.)



Subjects

Ss were undergraduates. The number of the Ss for each character and in each condition (the Competitive, the Irrelevant, and the Relevant) were 54, 53, 49 for /rui/, 54, 56, 55 for /kou/, and 57, 53, 56 for /ei/ respectively.

Procedure

RRW with each character was performed in three phonetic conditions as in Experiment 1; the Competitive, the Irrelevant, and the Relevant conditions. The activated character names in the Competitive conditions were those of the characters which appeared as slips most frequently in the preliminary RRW (see Figure 4). In the Irrelevant conditions, activated character names were those of the characters which did not appear as slips at all; /tetsu/ for /rui/, /taku/ for /kou/, and /hen/ for /ei/.

Results and Discussion

Slips made up to Ss by the 50th repetition were analyzed. Table 1 shows the mean number of slips and the percentage of the subjects who made a slip. The results showed the same trends as Experiment 1. In all three characters, the frequency of slips declined in this order: the Competitive, the Irrelevant, the Relevant condition. The effect of phonetic condition was significant for all the characters ($F(2,153)=4.7$, $p<.05$ for /rui/; $F(2,162)=3.7$, $p<.05$ for /kou/; and $F(2,163)=7.5$, $p<.01$ for /ei/). Tukey tests indicated that the Competitive condition caused significantly more frequent slips than the Relevant condition for all the three characters ($p<.01$ for each character). The irrelevant conditions caused more slips than the relevant conditions consistently. However there was no significant difference between the two conditions for any of the three characters. The Competitive condition caused significantly more slips than the Irrelevant condition only for /rui/ ($p<.05$) and for /ei/ ($p<.01$).

Table 1 The mean number of slips and the percentage of the subjects who had made any slip up to the 50th repetition (Experiment 2).

Character	Condition					
	Competitive		Irrelevant		Relevant	
	Mean N	% Ss	Mean N	% Ss	Mean N	% Ss
類 /rui/	3.5	70.4	1.5	49.1	0.8	36.7
香 /kou/	1.6	55.6	1.1	53.6	0.7	47.3
栄 /ei/	1.1	50.9	0.6	35.8	0.4	26.8

For all three characters and under all phonetic conditions, the most frequent slips were writing the competitive character (see Figure 4). Activation of irrelevant phonetic memories caused the slip of writing an irrelevant character only very rarely. Only one subject in the Irrelevant condition for /ei/ made the slip of writing the irrelevant character /hen/.

These results indicate that the findings from Experiment 1 with simple phonograms can be generalized to more complex characters, Kanji (Chinese-originated characters).

GENERAL DISCUSSION

We can recognize a general trend from the above experiments. For all the characters used in RRW, slips occurred most frequently in the Competitive condition, and least in the Relevant condition. In conditions where, unlike ordinary handwriting, the motor memory for a character is compelled to be dissociated, the motor memory might be liable to lose its control over writing behavior. When dissociation was accompanied by the activation of a competitive motor memory, slips were facilitated. On the other hand, slips were not inhibited completely even by activating the relevant phonetic memory. For example, more than half of the subjects made slips even in the Relevant condition for /o/. This suggests that, as hypothesized, the repeated use of a motor program causes the spreading activation of other motor programs.

Ellis (1982) proposed a comprehensive model for writing which is related to the causes of slips of the pen. His model would classify the slips of the pen caused by RRW as 'substitution errors (misselection),' and the slips are said to arise as a consequence of similarity between 'the spatial code (allographic code)' and the graphic motor pattern. Many question remain unexplained, however: Is an appropriate motor pattern replaced by another similar one in the course of execution of it even after the selection of the motor pattern? Is the selection of a motor memory necessary every time before its repeated execution, like in RRW? How are the memories of similar motor patterns organized in the motor pattern store?

Another interesting aspect of the effects of dissociation should be noted. The subjects in RRW usually reported that they came to feel an uncertainty as to whether the character they were writing was really correct or not. Moreover, in the Competitive and in the Irrelevant conditions, some reported a feeling of discomfort. Compelling the subjects to dissociate the motor memory from the closely connected phonetic memory by the activation of the irrelevant phonetic memory appears to have somewhat overloaded them.

The present investigation dealt with the linkage between motor and phonetic memories, and also with the linkage among motor memories of non-alphabetic characters, Kanji and Kana. In a non-systematic observation with Chinese subjects using the RRW technique, similar slips were found. When six subjects from Hong Kong were asked to perform RRW of Kanji /rui/, three of them made slips of writing Kanji /su:/ up to the 50th repetition as with Japanese subjects. Japanese and Chinese as well learn to write more than thousand characters. Many of the characters share common or similar segments of movements in writing. Non-alphabetic characters like Chinese or Japanese characters are thought to have some advantages, especially from their diversity when the linkage among motor memories is considered.

ACKNOWLEDGEMENTS

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FOOTNOTES

1. Nihei, Y. Experimentally induced slips of the pen. A paper presented at the International Symposium on Psychological Aspects of the Chinese Language, (Hong Kong, 1984).

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BETWEEN-LETTER CONTEXT EFFECTS IN HANDWRITING TRAJECTORIES

Arnold J.W.M. Thomassen
Lambert R.B. Schomaker

INTRODUCTION

One of the chief goals of our research into the motor control of handwriting is to develop a computational model describing the observed trajectories and their dynamics under normal and experimental handwriting conditions. Such a model would, furthermore, allow the prediction of handwriting phenomena in certain writers and under certain conditions which have as yet not been investigated. Finally, if implemented on a computer-controlled simulator, the model would generate genuine handwriting behavior much like a natural writer. Aiming at such a model has, of course, as its main purpose the accurate and exhaustive formulation in abstract terms of the many obvious and concealed problems in such a complex task. This will hopefully yield insights into general relationships and general action or control strategies in the execution of writing and other movements. To the extent that such a general, overall insight is not (yet) obtained, the computational efforts involved in simulating handwriting may still provide useful and instructive analogies of certain aspects of the task.

A typical feature of tasks such as speech, typing and handwriting is that they are concerned with complex physical anatomy, with highly practised motor skill, and with cognitive control structures dealing with the rapid succession of discrete linguistic units such as phonemes, key positions and graphemes which have stored representations in motor memory. Before going over to our own handwriting experiment, we shall make a small excursion into the study of context effects in speech and in typing that provide the basis for our hypotheses which also focus on context factors.

Coarticulation in Speech

In speech, the phenomenon of coarticulation refers to the fact that the various articulators do not jump instantaneously from one steady position to the next, corresponding to the successive speech sounds. Instead, these transitions are characterized by relatively slow movements. Consequently, even at a normal speech rate of, say, twenty phonemes per second, there is a considerable overlap between the successive speech sounds. Usually, several phonemes are being articulated at the same time. This results in complex 'coarticulatory' interactions amongst them, which — although they reduce the acoustic distinctiveness of the individual phonemes at their boundaries — in general enhance the intelligibility of the message. For example, the phonemes /k/ in *kick* are different from those in *cock* they carry information of the enclosed vowel. Coarticulation effects may occur even beyond adjacent phonemes, such as in /s/ in *street* vs /s/ in *stroke*. It seems as if the articulator movements producing the vowels are slow, so that they must start relatively early. Indeed, if a vowel is of very short duration, it has been shown (e.g., Lindblom, 1964) that its optimal position is in fact never reached. But typical coarticulation effects occur among consonants as well, such as in *rainbow* where /n/ is assimilated to /m/, which anticipates the bilabial articulation position of /b/. In this respect it is of interest to note that speech synthesis is most successful when the stored and retrieved units are not the individual phonemes, but rather their successively paired 'diphones' in which specifically the coarticulation effects for the transition from one phoneme to the next are wholly maintained. Obviously, the extent to which coarticulation occurs depends on the speaker, on the degree of effort he spends on his articulation, and on the rate of his speech. It should be noted, of course, that not all adjacent phonemes are coarticulated to the same extent; conflicting movements by the same articulators are difficult to perform simultaneously, whereas movements by independent articulators, such as lip rounding in /o/ and tongue alveolarisation in /s/ of *stroke* may readily occur together.

Context Effects in Typing

Similarly, in highly skilled typing, coarticulation effects are known to exist. Such rapid typing, where rates of about 10 strokes per second are reached, is characterized by parallel output performance, and not by the serial production of one letter at a time. At the output level it can be observed that hand and fingers start to move towards the intended keys even before several intervening keys have been touched (Gentner, Grudin, & Conway, 1980). Apparently, there is a coordinating mechanism which takes care of the control of several fingers simultaneously, solving conflicts among direction instructions to reach the successive key positions in the correct order. Such a mechanism would in a flexible way make use of the large number of degrees of freedom of hand and finger movements in attaining spatial target positions. It is considered most likely by these authors that the solutions are achieved mainly by local computations and in parallel rather than by a single central mechanism. The timing aspects of execution are also thought dependent on the physical properties of the hand and finger motions rather than on a central time-controlling mechanism (Norman & Rumelhart, 1983; Rumelhart & Norman, 1982). A typical finding in the research of typing, similar to the difficult and easy coarticulations mentioned above, is that sequences involving relatively independent effectors (such as alternations between hands) are performed most rapidly, whereas the repeated activity of the same effector (such as the same finger typing two successive letters) is slowest.

Context Effects in Handwriting

In the framework of our attempts to arrive at a computational model of the handwriting process, an astonishing number of questions need to be answered. These are not only concerned with the central representational and coordination structures referred to above, but also with the latter more peripheral effects occurring during the actual performance of retrieved representations from motor memory. Before any phenomena are considered to be computed at the highest levels, their origin should indeed be sought at lower levels to see whether they may result from local computation or merely from the mechanics of the effector system. It will often be difficult to decide between the latter two, or even to discriminate these from central factors. However, in the study of handwriting it is to be expected that, once the allographs have been selected, individual graph realizations are subject to local or mechanical effects. The context effects that constitute the topic of the present paper are to be localized at these 'lower' levels.

It is hypothesized that, in analogy with speech and typing, selected allographs are performed as a function of the surrounding allographs, i.e., that the production of graphs (individual realizations of allographs) depends on the preceding and following graphs. Within a graph, we have found earlier (Thomassen & Teulings, 1983; Maarse & Thomassen, 1983) that down strokes constitute the most invariant core, whereas up strokes, which often act as connecting strokes, necessarily reflect transitions of various kinds. But it is still to be expected that even the production of down strokes is affected by the context, similar to the vowel production in speech discussed above.

Earlier Work

Within-word context effects in handwriting have been investigated by Wing, Nimmo-Smith and Eldridge (1983). Their intention was to investigate the suggestion made by Ellis (1979) that the selection of the specific form of a grapheme (i.e., allograph selection from motor memory) is influenced by the immediately preceding graphemes. Wing, et al. let their subjects write a text six times. The target letters could occur in initial, middle, or final positions in the word. If not preceded or followed by a space (initial and final positions, respectively), they were preceded and followed by constant graphemes. These authors looked at the variability of letter forms (allographs) as a function of their position in the word. They observed that graphemes in initial positions were written less consistently than in the middle or at the end of the word, the effect being entirely due to the first up-stroke of the word. It was concluded that the preceding 'space' context provides less constraints, and therefore produces more varied allograph selection, than the constant grapheme does. In other words, the preceding grapheme in part determines the selection of the next allograph. It should be noted, however, that the observed differences occurred in only a small proportion of the cases and was limited to the single stroke preceding the first down stroke of initial letters.

Present Study

Our study differs from the experiment by Wing, et al. (1983) in a number of respects. Firstly, we are not interested in the selection of allographs; in fact, our subjects were instructed to use constant allographs in their handwriting and they rejected a trial if a different allograph still occurred. Instead, in the present study we concentrate on graph performance, i.e., on the individual realizations of the same allographs as a function of their environment (between-letter context). We looked for systematic changes induced by context variations rather than for the mere presence or absence of consistency. Secondly, in line with the coarticulation effects and context effects in typing discussed above, we are principally interested in anticipations (rather than perseverations or 'aftereffects'). As a result, our study defines between-letter context not exclusively as the preceding grapheme (as in Ellis' hypothesis referred to above) but in most cases as the following grapheme. Finally, Wing, et al. looked at the written product, i.e., at the writing trace, and they relied on qualitative judgments. In our study, in contrast, we look at the dynamics of the writing process (stroke duration) as well as at their spatial features (stroke size), always in a quantitative fashion. In an earlier study (Thomassen & Teulings, 1985) it was shown that size and shape features in various contexts bear specific relationships to the duration of the handwriting movements. The latter paper also summarizes earlier work on the relationship between size, curvature and duration (Denier van der Gon & Thuring, 1965; Greer & Green, 1983; Lacquaniti, Terzuolo, & Viviani, 1983; Wing, 1980) from which it appears that context effects in handwriting are most interesting in a dynamic sense.

Between-letter context effects may be expected to occur in many forms. The simplest ones, which are most likely due to local factors, are not structural but metric changes in a single stroke as a function of certain features of a neighbouring stroke, such as its curved or sharp ending, its direction or its length. In the present study, the most elementary graphemes, viz., *e* and *l*, are studied both as 'target' and as context graphemes. In a very simplified way, one might summarize the experiment as one in which stroke size is varied in both target and context. A different context is hypothesized to affect the execution of the identical strokes differentially. The context is provided by the following or preceding grapheme in all 16 four-letter combinations and permutations of *e* and *l*.

Although context effects may probably be observed beyond adjacent graphemes, similar to the coarticulation effects beyond phonemes in speech and context effects beyond the next key stroke in typing (see above), we shall, for the present purpose, concentrate on adjacent graphemes. We formulate three general assumptions which, following the introducion, need no further justification. (1) The motor system execution writing movements reacts relatively slowly. (2) Anticipatory and overlapping instructions to the motor system occur as a consequence. (3) Overlapping instructions to opposed muscle systems cause a decrease in the amplitude and velocity of the movement. On the basis of these assumptions we formulate the following hypotheses as regards the immediate context effects between adjacent graphemes in the four-letter sequences composed of the graphemes *e* and *l*. Our hypotheses have a bearing on the down stroke in the target grapheme as a function of the following or preceding context grapheme. Specifically, we predict size and duration effects on this down stroke.

Hypothesis 1

Writing a grapheme will be more sensitive to the grapheme which it precedes than to that which it follows.

Hypothesis 2

More rapid writers will display stronger context effects than slower writers.

Hypothesis 3

Due to the anticipation of the long up stroke of *l* in *el* (a) *e* will have a shorter down stroke in *el* than in *ee* and (b) *e* will have a shorter-lasting down stroke in *el* than in *ee*.

Hypothesis 4

Due to the anticipation of the short up stroke of *e* in *le*, (a) *l* will have a smaller size in *le* than in *ll* (b) *l* will have a longer-lasting down stroke in *le* than in *ll*.

Hypothesis 5

Identical repeated graphemes provide a 'neutral' environment and have no specific context effect on size. They will, however, be subject to the general decreasing trend within words in writers who display this trend, leading to a larger initial in *ee*, and to a larger initial l in *ll*.

Note that the predicted relationship between stroke size and stroke duration in these hypotheses is by no means trivial in the sense that a shorter duration would always be associated with a smaller stroke. In Hypothesis 3, this relationship is indeed expected because in *el* the shorter down-stroke duration in *e* is supposed to result from the early onset of a movement in the opposite direction due to the force requirement involved in producing an opposed, tall up stroke immediately following it. In contrast, in Hypothesis 4 a shorter down stroke is predicted to be brought about in *le* by a longer-lasting movement. Here we have an *l* up stroke of a large size to begin with. Its goal position is, however, not completely reached because its size is reduced in anticipation of the smaller size of the *e* to follow. There is, furthermore, a decreased force in the down stroke in anticipation of the low force level associated with *e* (Assumption 3).

METHOD

Subjects

Two adult right-handed male subjects, aged 28 and 49, participated in the experiment. Both subjects were researchers with experience in the laboratory study of handwriting.

Materials

The movements of the tip of the writing stylus were recorded by means of a large-size writing tablet (Calcomp 9000) connected to a computer (PDP 11/45). The laboratory-made writing stylus was of near-normal weight and dimensions except for the presence of a small pressure-tranducer encasement protruding (away from the subject's hand) from the side of the barrel, and of a light-weight flexible wire leading from the barrel's top to the computer. The stylus contained a normal ball-point refill. Thirty-eight pseudowords were printed on the specially prepared A4 response sheets in twelve rows of two to five words each. A row contained a certain 'family' of pseudowords allowing specific comparisons. Thus, there were four rows each containing four of the 16 different four-letter pseudowords that can be made up of *e* and/or *l*. These rows themselves were placed in a quasi-random order. Data on the eight other rows which were concerned with within-letter context effects, will be reported elsewhere.

Procedure

The subjects' task was to write on the response sheet immediately below the place where the pseudowords were printed. The response sheet was placed vertically on the writing tablet in a convenient position and at a preferred angle. The sheet was held by the subject's left hand just as in a normal writing situation. The subject's right lower arm rested on the writing tablet. A pseudoword had to be written fluently without raising the pen. There were no constraints as to pen movements and paper shifts before and after writing each of the successive pseudowords. This was done in a natural, constant order from left to right and down the page.

A session consisted of writing the 38 pseudowords once. An experimenter-controlled tone sounded to signal the onset of a 2.5 s. period during which the writing could be produced. Two tones signalled the end of the interval. The experimenter took care that he did not start the interval until the subject's hand rested in approximately the appropriate position for the next word. If the subject was not satisfied, due to hesitations, errors (e.g., selection of incorrect allographs), jerks, late starts or slow movements, he was immediately given another trial in which the word was written below the rejected product. A session, which lasted only four minutes, could be followed by a further session after a rest of a few minutes, or sessions could be separated by a whole day. Each subject completed ten sessions.

Signal Processing

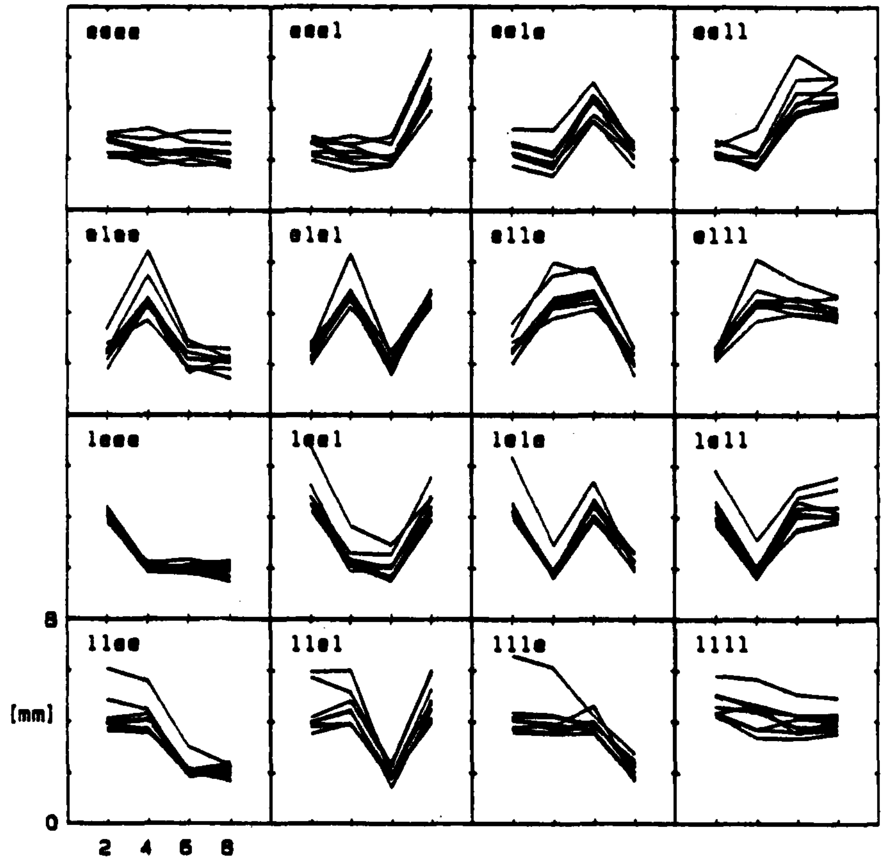
The X and Y-coordinate values and the pressure at the tip of the pen (Z coordinate) were sampled at a 105 Hz rate, samples having an accuracy of 0.02 mm. in both X and Y directions. For further details see Schomaker & Thomassen (1985) in the present volume.

RESULTS

During processing of the records stored in the computer, two files of both subjects went lost in an aselect manner. Therefore, the data to be presented are based on only eight replications per subject. All their X and Y data were processed and entered into the analyses without any further selection of outlyers or oddities. As indicated above, the analysis was confined to features of the down strokes, i.e., to the four even numbered strokes (2,4,6,8) in each pseudoword.

If we first look at the data in a qualitative fashion, comparing Figures 1 and 2, we see that the variation over the eight replications is smaller in the space domain (vertical stroke size) than in the time domain (stroke duration) in both subjects. This confirms other findings in our laboratory as reported in the present volume (Teulings, Thomassen, & Van Galen, 1985). The spatial features in an allograph apparently display greater constancy than the temporal features (Note 1). Furthermore, durations seem to reflect context effects to a greater extent than sizes do. This is obvious from a comparison of certain patterns in Figure 2, where there is much more "rounding off" between stroke durations than there is between sizes in Figure 1. (See e.g., *elle, elll*). Now looking at the two subjects separately, we find that Subject 1 is slightly more variable both in sizes and durations than Subject 2, but in both subjects the different patterns are quite specific for the 16 different pseudowords. The most important analysis concerns the comparisons of the same graphemes written in different context, i.e., of *e* written immediately before or after *e* or *l*, and of *l* written immediately before or after *e* or *l*. The size results are summarized in Table 1, where subjects' median values for each pseudoword are averaged across the 12 occurrences of each letter in

Figure 1a Vertical size of the four down strokes in eight replications by Subject 1 of 16 different pseudowords.



each context. Table 2 presents the duration results, in which the subjects' mean values for each pseudoword are averaged over the same 12 occurrences of each letter in each context.

Figure 1b Vertical size of the four down strokes in eight replications by Subject 2 of 16 different pseudowords.

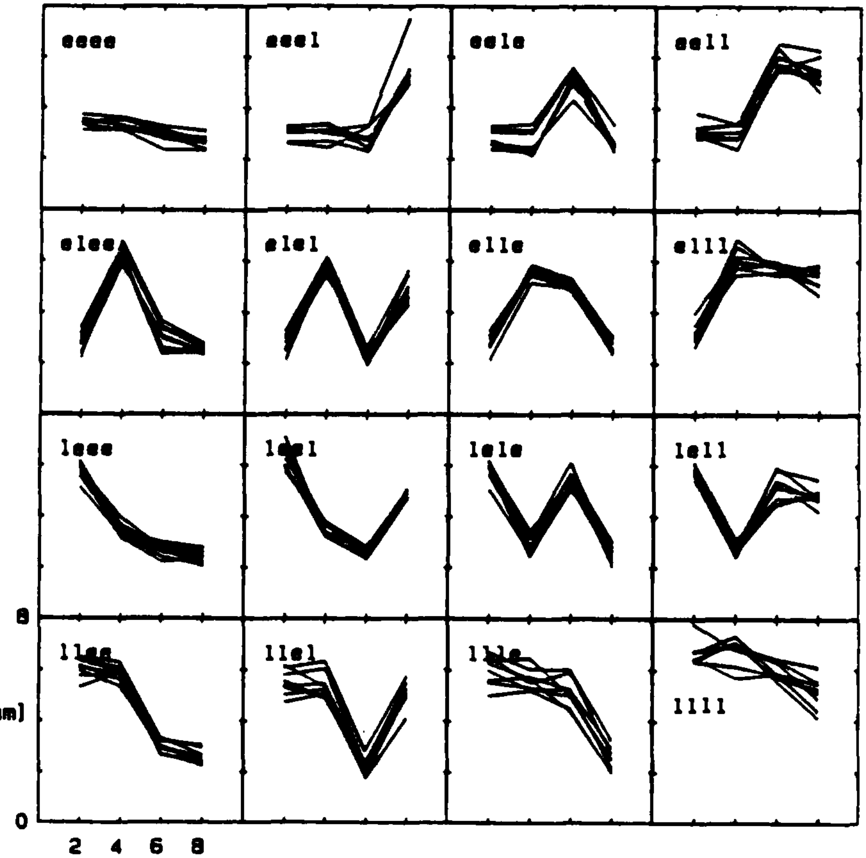


Table 1 Averaged median values of vertical stroke size (mm.) of e and l (target) in different context.

	Target precedes context				Target follows context			
Target:	e		l		e		l	
Context:	e	l	e	l	e	l	e	l
Subj.								
1	2.28	2.10	4.37	4.21	2.11	2.08	4.50	4.22
2	3.20	2.63	5.67	5.93	2.76	2.74	5.46	5.50

Figure 2a Duration of the four down strokes in eight replications by Subject 1 of 16 different pseudowords.

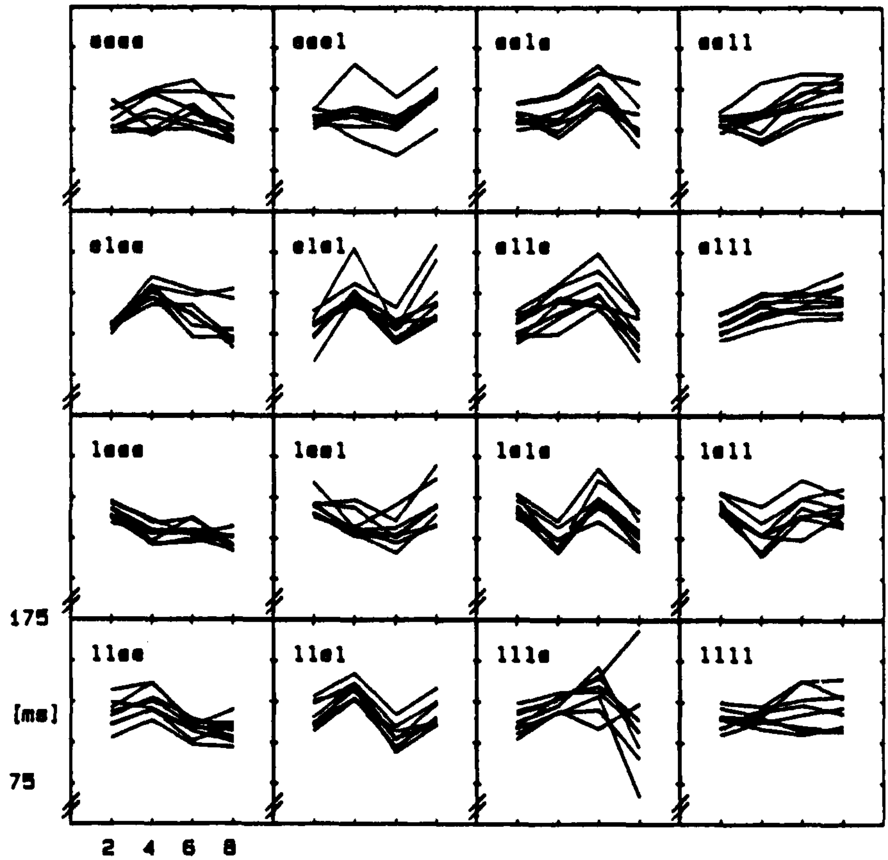
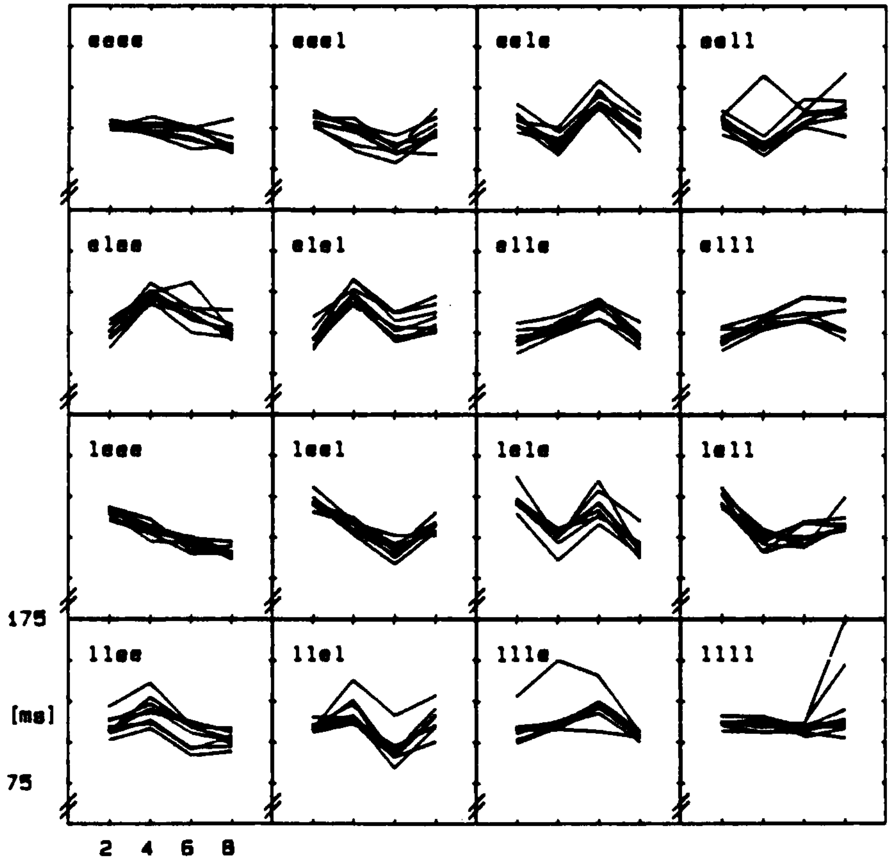


Table 2 Averaged mean values of vertical stroke duration (ms.) of e and l (target) in different context.

	Target precedes context				Target follows context			
Target:	e		l		e		l	
Context:	e	l	e	l	e	l	e	l
Subj.								
1	108	104	125	117	106	105	122	123
2	103	96	121	109	96	101	111	115

Figure 2b Duration of the four down strokes in eight replications by Subject 2 of 16 different pseudowords.



Figures 3 and 4 display these data separately for each subject across the appropriate serial positions (stroke numbers) within the pseudowords. In their left-hand panels, moreover, these figures present the overall features of *e* and *l*, irrespective of context, across the stroke positions in the pseudowords, as well as their averages. We shall refer to these tables and figures when discussing the results in terms of the hypotheses we formulated above. Testing the hypotheses is done by a nonparametric procedure (Wilcoxon matched-pairs signed-ranks test). The relevant pairs are generally pseudowords that are identical except for the critical context grapheme (e.g., *eeee* vs. *eele* to test the anticipation effect of *l* on *e* in the second position). This yields 12 paired comparisons in all cases.

Figure 3a Median values and their mean of the vertical size of the down strokes in *e* and *l* as a function of their serial stroke number (left-hand panel), and as a function of their context; target grapheme preceding its context grapheme (central panel); target grapheme following its context grapheme (right-hand panel). Subject 1.

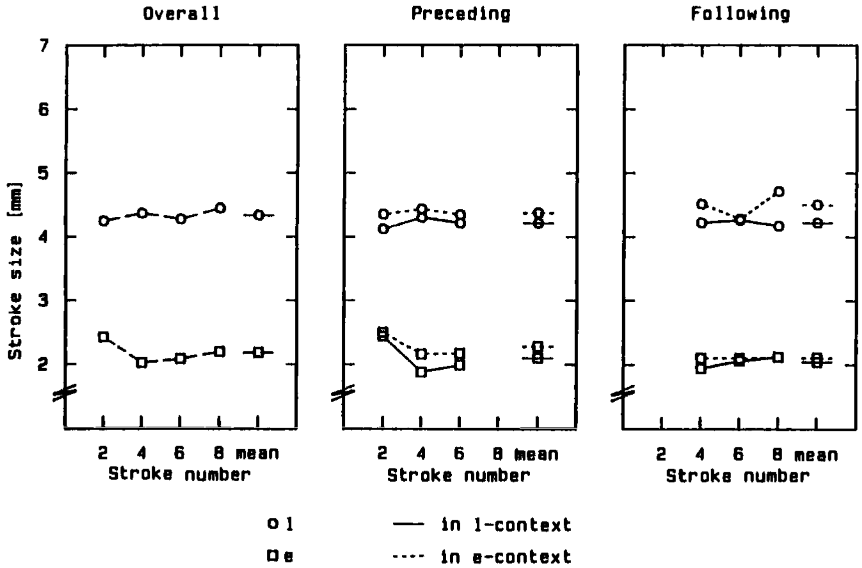


Figure 3b Median values and their mean of the vertical size of the down strokes in *e* and *l* as a function of their serial stroke number (left-hand panel), and as a function of their context; target grapheme preceding its context grapheme (central panel); target grapheme following its context grapheme (right-hand panel). Subject 2.

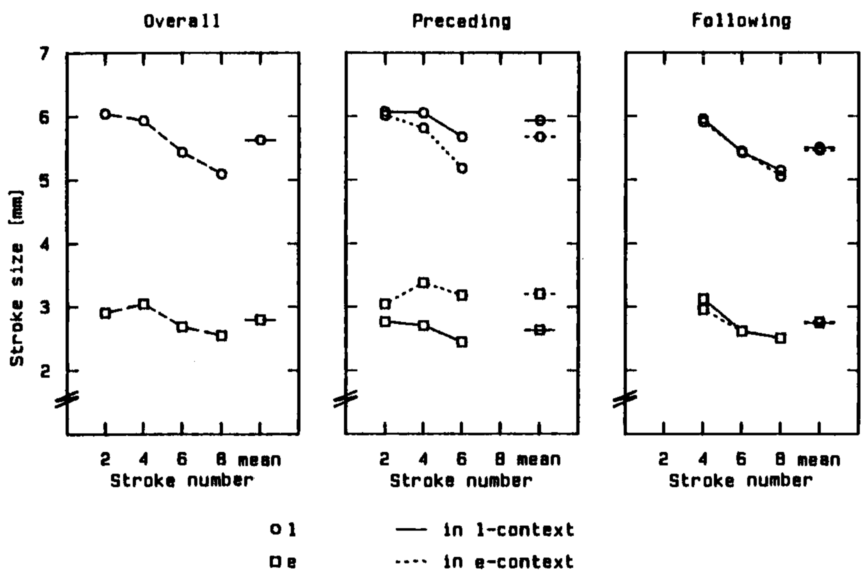


Figure 4a Average values and their mean of the duration of the down strokes in *e* and *l* as a function of their serial stroke number (left-hand panel), and as a function of their context; target grapheme preceding its context grapheme (central panel); target grapheme following its context grapheme (right-hand panel). Subject 1.

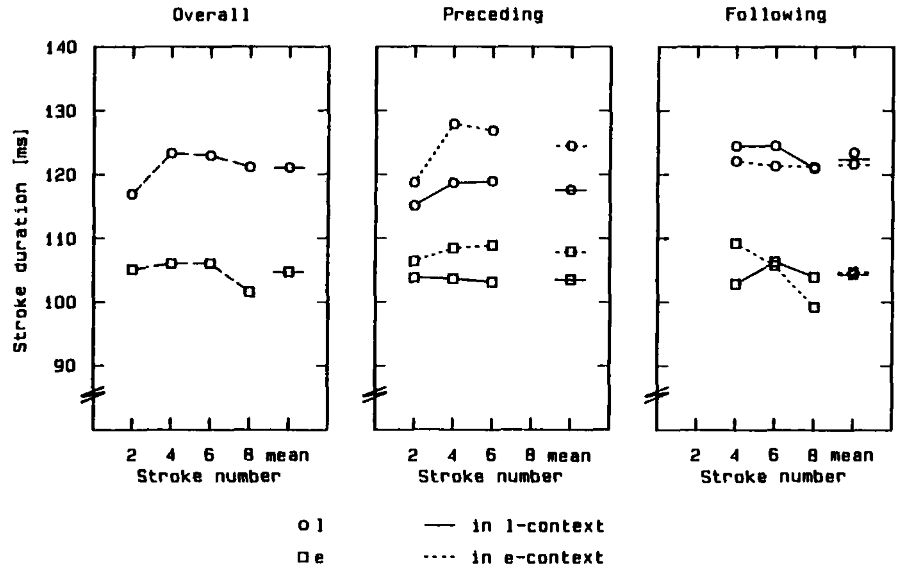
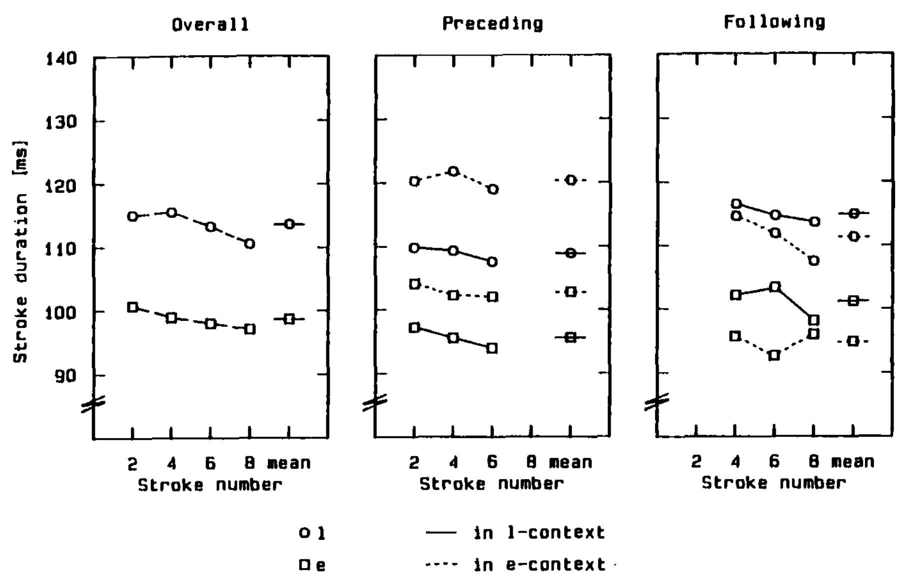


Figure 4b Average values and their mean of the duration of the down strokes in *e* and *l* as a function of their serial stroke number (left-hand panel), and as a function of their context; target grapheme preceding its context grapheme (central panel); target grapheme following its context grapheme (right-hand panel). Subject 2.



Hypothesis 1

From Figures 3 and 4 it can be seen that both in the time domain and in the space domain, the 'anticipatory' context effect on a preceding adjacent grapheme is stronger than the 'aftereffect' on a following adjacent grapheme. For duration, the mean effects are 7.75 ms. and 2.75 ms., respectively, and for size, the mean effects are 0.29 and 0.09 mm. These differences in the expected direction, which are present in both subjects, are significant ($N=12$; $T=3.5$; $p<.005$ and $N=12$; $T=17$; $p<.05$).

Hypothesis 2

Subject 1 has a mean stroke length of 3.25 mm. His mean stroke duration is 113.75 ms. His writing velocity in down strokes, therefore, is 28.57 mm/s. Subject 2 has a mean stroke length of 4.21 mm. His mean stroke duration is 106.50 ms. The resulting writing velocity in down strokes is 39.53 mm/s. Thus, the writing speed of Subject 2 is considerably higher than that of Subject 1. The expected difference in context effects displayed is indeed observed. In Subject 2 the effects in duration and size are 7.00 ms. and 0.22 mm. respectively, whereas in Subject 1 they are only 3.50 ms. and 0.16 mm. The duration difference is very significant. ($N=12$; $T=6,5$; $p<.005$). For size effects there is only a significant difference between the subjects where the target letter precedes its context ($N=6$; $T=2$; $p<.05$). As regards the 'aftereffects' on size, where the target follows its context, there is no significant difference between the subjects.

Hypothesis 3a

The expected effect on the down stroke in *e* as a function of *e* or *l* following it is indeed observed. In Subject 1 the mean size of *e* preceding *e* is 2.28 mm.; of *e* preceding *l* it is 2.10 mm. The 0.18 mm. difference is highly significant (Wilcoxon matched-pairs signed-ranks test; $N=12$, $T=6$, $p<.005$). In Subject 2 the effect is even bigger. The sizes here are 3.20 and 2.63 mm., the difference being 0.57 mm and highly significant ($N=12$; $T=4$; $p<.005$).

Hypothesis 3b

The expected duration effects are likewise present. Subject 1 takes 108 and 104 ms. to produce the *e* downstroke in the two context conditions. Subject 2 takes 103 96 ms. These differences in the expected direction of longer duration in *e* preceding *e* than in *e* preceding *l* are both significant ($N=12$; $T=1$; $p<.005$ and $N=12$; $T=0$; $p<.005$). From Figures 3 and 4 it may be concluded that the effects both on size and on duration are on average present in all relevant grapheme positions (stroke numbers 2, 4 and 6) in both subjects. An illustration that, nevertheless, the size effect may have different origins is seen in Figure 5, representing one realization of the pseudoword *eele* by each subject. Both subjects produce a smaller *e* immediately preceding *l*.

Comparing the second and third down strokes we see that Subject 1 in this particular case reduces velocity rather than duration; Subject 2, on the other hand, follows the predicted and observed average strategy by reducing *e* down-stroke duration in favour of a lengthened *l* up-stroke duration.

Figure 5 Realizations of the pseudoword *eele* by two subjects, together with their y-velocity profiles. (The durations of the entire realizations are normalized; down-stroke velocity appears below the zero-velocity line, up-stroke velocity above the line).

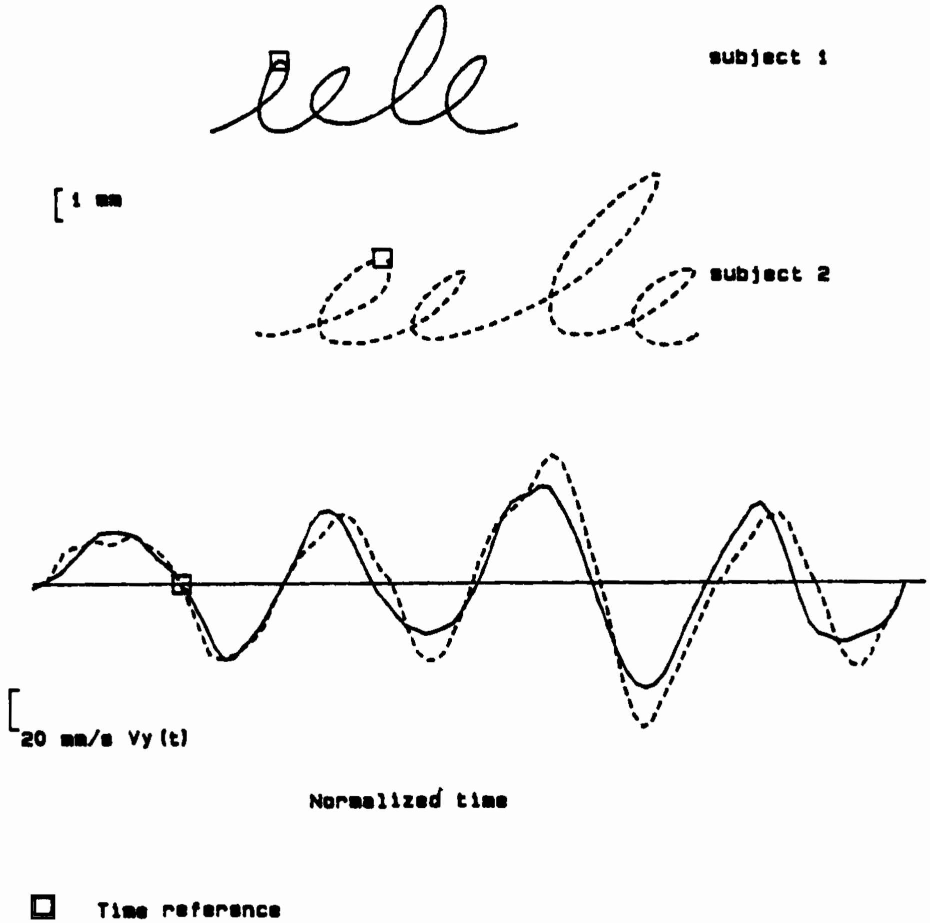
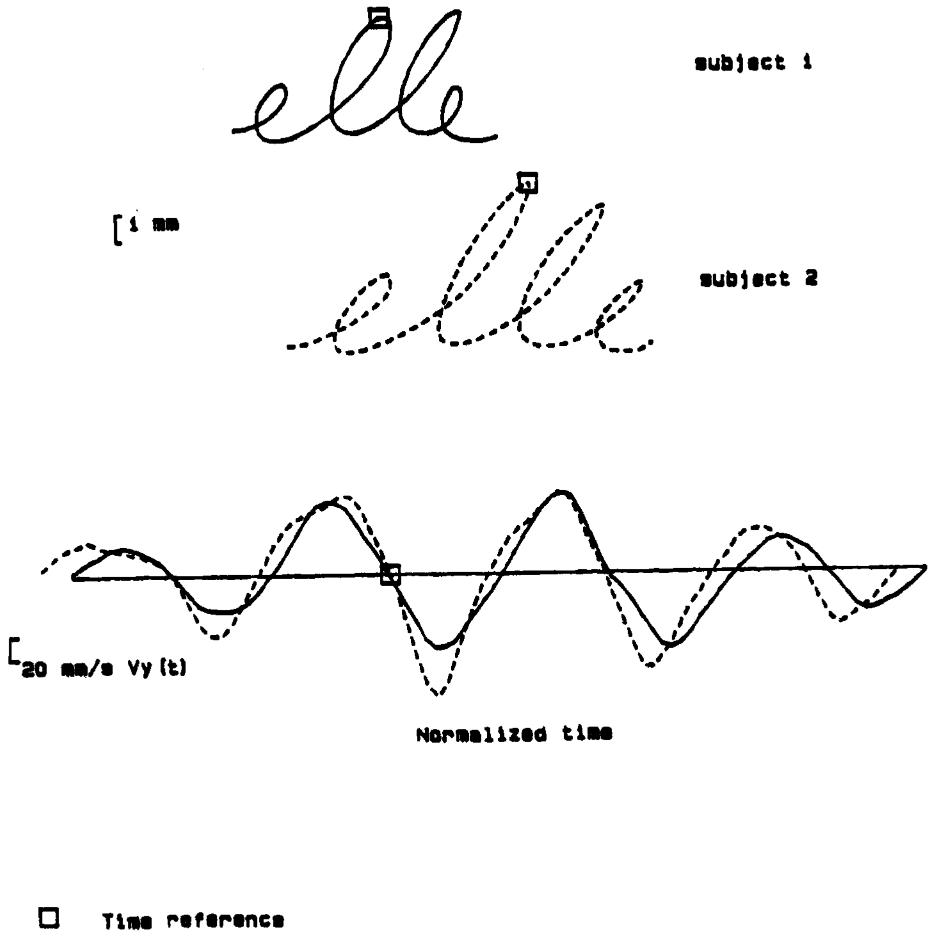


Figure 6 Realization of the pseudoword *elle* by two subjects, together with their y-velocity profiles. (The time-normalized profiles show that in Subject 1 the third down stroke takes more time than the second down stroke, whereas in Subject 2 it has lower velocity).



Hypothesis 4a

The predicted size effect on the *l* down stroke as a function of *e* or *l* following this grapheme is not observed in Subject 1. In fact, his *l* is almost significantly longer when it precedes *e* than when it precedes *l* (4.37 and 4.21 mm., respectively. N=11; T=11.5; p=0.6). Subject 2, moreover, only produces the expected difference as an average, his sizes being 5.67 mm. for *l* in *le* and 5.93 for *l* in *ll*. The latter effect fails to be significant (N=12; T=24; p.05).

Hypothesis 4b

The effect on stroke duration is again significantly present in both subjects. The down stroke in *l* takes considerably longer when *l* precedes *e* than when it precedes *l*. The mean values here are 125 vs. 117 ms. in Subject 1 and 121 vs. 109 in Subject 2 ($N=12$; $T=2$; $p<.005$ and $N=12$; $T=0$; $p<.005$). To the extent that Subject 2 does produce a shorter *l* down stroke in a longer duration his velocity must be considerably reduced. This can be observed for this subject when comparing the second and third down strokes in Figure 6, showing individual realizations of the pseudoword *elle*.

Subject 1, whose second *l*, immediately preceding *e*, tends to increase rather than decrease, achieves this effect in the present example by an extra lengthening of the down-stroke duration in the current grapheme, holding velocity constant.

Hypothesis 5

The left-hand panels of Figure 3 display the fact that there are differences between subjects as regards the size decline within words. Subject 1 shows no sign of this effect, whereas it is clearly present in Subject 2; estimates of his general decline in *e* and *l* are 0.15 mm. and 0.30 mm. per letter respectively, i.e., of the order of 5 percent of the letter size. When comparing adjacent alternations to doubles of *e* and *l* we do not observe any specific differences in size due to the fact that a grapheme occurs twice in succession. In Subject 1, as may be seen from Figure 3a (central and right-handed panel), repeated *l*s are both written slightly smaller but repeated *e*s are both written slightly bigger than these letters in alternating positions. As regards Subject 2, we observe in the central panel of Figure 3b that *l* and *e* are both taller when they are the first letter of a double than when they alterate with *e* and *l* respectively. These differences are accounted for by the other hypotheses, however. Moreover, from the right-hand panel of Figure 3b it is obvious that the size of a grapheme following an *e* or an *l* is not at all affected by its preceding occurrence. This implies that the size decline in 'doubles' in this subject merely reflects his general trend across the word, which is in line with Hypothesis 5.

DISCUSSION

We have seen that the variation in durations and sizes of strokes, both within and between subjects, can, at least for its major part, be explained by a limited number of factors. Four out of the five hypotheses derived from our assumptions were confirmed. We may conclude that anticipations dominate over aftereffects (Hypothesis 1), and that high writing velocity goes together with stronger anticipation effects (Hypothesis 2). Certain size and duration effects can be predicted well (Hypothesis 3), although duration effects are generally more sensitive and easier to predict than size effects

(Hypothesis 4). In general, individual differences appeared to be larger than anticipated. Moreover, individual variability, and flexibility in attaining specific letter sizes, appeared to be considerable, as was also illustrated by Figures 5 and 6. In view of the short durations (110 ms.) of the strokes and of their single-burst nature, a feedback explanation is out of the question here. It may be, however, that forces and their durations are adjusted in advance, in anticipation of opposed forces related to strokes further on. Such a (learnt) strategy would reduce size overshoots and underachievements, which would favour the constancy (and legibility) of the handwriting trace.

For the production of a written word our results imply that, once the allographs have been selected form motor memory, and their overall size adjusted, their production is subject to a number of local influences on size, but more so on duration, in which velocity levels and directions and their anticipation play a central role. This conclusion is in line with our earlier findings (Thomassen & Teulings, 1985). Because generally anticipations are quite distinct, it must be concluded that the organisation of the motor sequence at a higher level activates several muscle groups in advance, probably in the correct order but with relatively long time constants, so that at any moment several muscle groups contract simultaneously, though with different onset and offset times. In spite of the mentioned possibility of anticipated compensation, the result is that, similar to the discussed coarticulation effects, certain 'target positions' will not be reached, or, similar to typing context effects, the trajectories towards them will be slowed down.

The fact that both the systematic and the unexplained (noise) effects on duration are much more pronounced than those on size, is in agreement with repeated findings in our laboratory (see Teulings, Thomassen & Van Galen, 1985). In the present discussion, special attention must be paid to the possible interpretation that some of this 'noise' is due to the fact that subjects tend to produce equal time intervals, across *e*s and *l*s, for which a timekeeping mechanism might be responsible. As indicated above, the duration data in Figure 2 are indeed more smoothed across the *l-e* transitions than are the size data in Figure 1. Most likely, this is not the result of a scaling difference between these figures because the scale in the duration and size plots are reasonably matched (Note 1). However, in some cases there is a much sharper distinction between the durations of *e* and *l* (e.g., in *lele* and *elel*, with single occurrences of *e* and *l*) than in other cases (e.g., in *leee* and *elll*, involving runs of three occurrences of *e* and *l*). It could be that in the latter instances, as well as in *eeee* and *llll*, which are more like scibbling patterns than like writing, there is a tendency to produce a periodic sequence in which larger and smaller letters are produced in approximately the same amount of time.

Above, we noted that it is likely that context effects can also be observed beyond adjacent graphemes. These effects have not been investigated here. Similarly, there may be context effects of an even 'higher' order. The general finding serving in our fifth hypothesis and strongly present in Subject 2 in the above experiment, namely the 'word' context inducing an approximately 5-percent smaller size of each following letter within words, was taken for granted in the present study. As an unexplained context effect, however, it certainly needs clarification (See Maarse, Schomaker & Thomassen, 1985).

FOOTNOTE

1. If we adhere to the movement formula *s=f**a*t**2, where s is size, *f* is a near-constant parameter describing the efficiency of an acceleration pattern, a is the (absolute) top acceleration in the stroke, and *t* is the duration of the stroke (Thomassen & Teulings, 1985), we note that a duration change by a certain factor corresponds to a size change by the square of that factor. If, as is representative for our data, stroke duration changes from 100 to 125 ms., (i.e., by a factor 1.25) stroke size would consequently change by a factor 1.25**2 = 1.5625, or from approximately 3.1 to 4.9 mm., if a is assumed to be constant. Or, in other words, in the middle of the scale in our Figure 2, the 25 ms. change should correspond to a 1.8 mm. size change in Figure 1. In fact, 25 ms. in Figure 2 is represented by the same distance as the representation of approx. 2.0 mm. in Figure 1. Near the middle of the scale there is thus reasonable equivalence. If anything, size is slightly overrepresented.

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Graphonomics: Contemporary Research in Handwriting
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WRITING TIME OF DOUBLE-CHARACTER CHINESE WORDS: EFFECTS OF INTERRUPTING WRITING RESPONSES

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INTRODUCTION

For complex psychomotor tasks such as speech, typing and handwriting, a memory actual movements are executed. This idea, commonly referred to as the motor program, can be traced back to Henry and Rogers (1960) who introduced the "memory drum" theory of movement control. The idea was that the practice effect was to 'carve in' a pattern of response much like the grooves on a phonograph record (Pew, 1984). More recently, the computer program is a more popular analogy for motor programs and the idea has been studied widely over a variety of motor tasks: typing and speech (Sternberg, et al., 1978); and even movements of other species (Wilson, 1961).

However, with regard to such a concept of stored motor representations, there are a number of controversial issues, of which two are particularly relevant to the present study. The first issue is the debate on whether a multilevel, hierarchical model or a single level model is responsible for motor control. When the idea of motor program was first suggested, it was assumed that movement commands would be planned and structured in advance. They are supposed to be stored in a temporary memory and executed in an open-loop manner, i.e., the information generated from central sources is supposed to be sufficient for the control of motor movement and no peripheral information would be required. As the view could not satisfactorily address oppositions like storage limitations (Schmidt, 1975, 1976) and variability of motion (Glencross, 1980), a change was called in the model so as to reduce the burden of the more central centres (Brooks, 1979) and a hierarchical model came out as a result. Keele (1981) suggested that the general features of the control representation are broken into more specific components until the lowest levels act to specify muscle activation. In 1983, van Galen and Teulings proposed a three-stage model for movement preparation: firstly, an abstract motor program is retrieved from the long-term motor memory; secondly, certain parameters like actual size and speed are substituted into the abstract program; and finally, appropiate motor units are recruited for motor execution. More recently, Rosenbaum and Saltzman (1984) proposed a model of a motor-program editor in which decisions for movements in choice RT tasks are assumed to be made in a hierarchical manner. When the response is called for by the 'go' signal, the required subprogram would be taken out and the missing features which are necessary for distinguishing alternative responses are then substituted before the response is executed. According to Stelmach and Diggles (1982), a hierarchical system could offer an explanation to the anomalies of movements like motor equivalence and variability of movement. Besides 'vertical interaction', 'distributed control' or horizontal interaction between units on the same level is also thought to be present in carrying out the commands in the stored representation.

The second relevant issue is the degree to which full movements are programmed prior to movement onset. Possible answers range from complete programming of the whole sequence at one end, through parallel execution of earlier strokes and programming of latter strokes at the middle, to totally on-line preparation, i.e., each sub-unit is prepared after the last one has been executed, at the other extreme. In the model proposed by Sternberg, et al. (1978), the whole movement sequence was assumed to be prepared in advance and stored as a collection of subprograms in a motor memory buffer. After the 'go' signal has been detected, the correct subprogram is then taken out from the buffer and unpacked into its constituents. The final stage is the command stage in which commands are issued to bring out execution of the constituents of the unit. The search and the unpacking of the subprogram for the subsequent unit are thought to be carried out in parallel to the execution of the preceeding motor unit. Also, in the paper written by van Galen and Teulings (1983), it was found that it took 9 msec longer to write the long, first upstroke of the letter 'h' when it was performed in the normal forward manner than it was performed in the reverse order. Again, the reason suggested was that the movement times of the earlier parts of a grapheme are increased as unpacking for the later strokes is done in parallel to the execution of these earlier parts. Another consequence of this view is that the execution of earlier parts would facilitate (shorten the writing times of) later strokes as compared to situations wherein these later strokes are executed as separate units. Given that this speculation is true, one of the aims of the present experiment is to see if such a facilitation effect can also be found in the writing of double-character Chinese words.

The major aim of the present experiment is to uncover analogous phenomena during the execution stage of the writing of Chinese characters.

Through studying the effects of interrupting the execution of a motor task by three different probe tasks: a positioning task (spatial level), a press button task (motor level) and a cognitive task, two major questions were investigated. Firstly, it studied the degree to which motoric movements are programmed before execution commences; and, secondly, whether the execution of motor movements can be differentiated into different levels of processing. These two questions were examined in the writing of double-character Chinese words. These Chinese words are composed of more than one component parts, which, by themselves, are meaningful Chinese words. For instance, ' 明 ' (meaning 'light') is made up of two parts: ' 日 ' (meaning the sun) and ' 月 ' (meaning the moon). It was hypothesized that if the unpacking process for the later strokes overlaps with the execution of earlier strokes, the total writing time for the whole character should be shortened if it is written continuously than if the left and right portions are written separately or if an interruption task is introduced at the middle of the writing. Moreover, if the stored motor representation is specified in different levels in a hierarchical manner during execution, interruptions aiming at disturbing the execution at various levels should have different effects on writing time. For instance, interruption at a more cognitive level would require the re-initialisation of the motor program to be begun at an earlier stage in the processing. Therefore, writing time of the subsequent portions would be longer in this case as compared to a situation where the interruption is at a more peripheral level, e.g., the motor level. As aforementioned, three types of interruption were included in this experiment. In the first type, a disturbance in the spatial positions of the two parts was introduced. Secondly, interruption at a motor level was introduced by asking the subject to press a button during writing. Thirdly, the disturbance is at a more cognitive level in which the subjects were asked to calculate a simple arithmetic problem in the middle of writing a word. In additon to the type of interruption, two other independent variables, familiarity and complexity of the word, measured in terms of its frequency and number of strokes respectively, were also included. As Pew (1966) successfully found evidence supporting that the learner develops more efficient motor program as a function of practice, it was assumed that high familiarity would facilitate the perceptual stage, the retrieval of the motor program or even the co-ordination of movements and hence results in a shorter writing time. Also, it was expected that effects of interruption tasks would be less distinct in writing high-frequency words. Contrary to this, for more complex words (more strokes), the programs are more complicated and, once interrupted, it would take a longer period to re-initialise the program. Therefore, the effect on the writing times of more complicated words would be greater than that on simpler words.

METHOD

Subjects and Design

Sixteen right-handed male and female undergraduate students from the University of Hong Kong participated as subjects. All of them were native

Chinese speakers and had taken the subject Chinese language in the Hong Kong Certificate of Education Examination. Each subject was verbally instructed to write twelve double-character Chinese words with the number of strokes and the frequency of the left portion, the right portion and the whole word systematically manipulated as independent variables. For each word, there were nine proper trials and the following is a description of them:

i) only the left portion was written;
ii) only the right portion was written;
iii) the whole character was written continuously (this serves as the baseline level);
iv) the right portion was displaced 10 cm to the right of the left portion;
v) the right portion was displaced 10 cm to the left of the left portion.

From the sixth to the ninth trial, right after the accomplishment of the left portion, the subjects were required to perform a simple task before they could continue with the right portion:

vi) a button was pressed once;
vii) a button was pressed twice;
viii) a simple arithmetic problem with a single plus operation (e.g., 3 + 4) was presented and the subjects were required to work out the answer;
ix) the arithmetic problem in (viii) was replaced by a more complicated one similar to '(3 + 4) × 2' and the rest followed (viii).

The order of performing these nine trials was randomised for each word.

Apparatus and Stimuli

Subjects were seated comfortably and all characters were written on an aluminium writing plate (18 cm × 5 cm) located at the centre of a wooden writing platform. Attached to the writing plate was a linear pressure transducer which was in turn connected to an APPLE IIe computer via a modified model of an electronic handwriting analyser (Kao, et al., 1969) and the triggering force on the plate to activate the system was set at 20 gram force. To measure writing time, the computer would measure the time interval between the first trigger point and the last one (the one not followed by any other pressure value higher than the triggering force in 500 msec). A common ball-point pen was used by the subjects throughout the whole experiment.

Twelve double-character Chinese words were employed. Low stroke words were those less than ten strokes whereas high stroke words were taken as those with more than twenty strokes. Frequency of the characters was determined according to Liu, Chuang and Wang's (1975) marginal frequency counts. Characters with a recorded frequency higher than 130 were considered as high frequency character while those less than 25 were considered as low. The twelve chosen characters are shown in Table 1.

Table 1 Stimulus words used in the Experiment.

	Number of Strokes	
Frequency	Low	High
HHH		
LHH		
HLH		
LHL		
HLL		
LLL		

Note:

* The leftmost letter indicates the frequency of the left portion, the middle letter represents the frequency of the right portion and the rightmost letter shows the frequency of the word as a whole.

The order of writing these words was counterbalanced with respect to their frequency and number of strokes.

Procedure

The subjects were instructed to write as clearly and as accurately as possible. At the start of the experiment, a trial character (該) was used to illustrate the requirements for each character. Prior to each word, five practice trials were provided for the subjects to familiarise with the word. The nine trials for that word were then performed one by one. The same procedure was repeated until all twelve words had been finished.

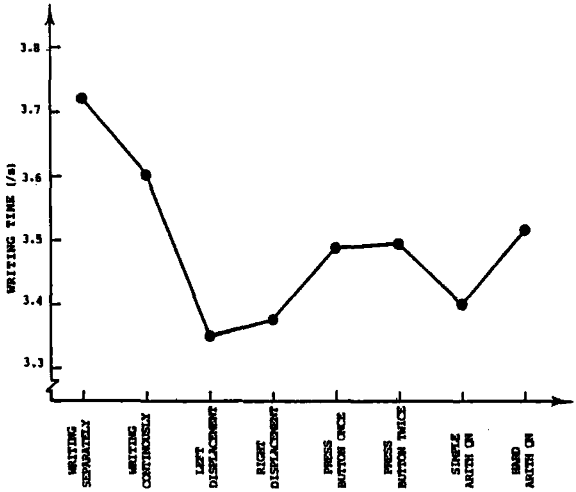
Data Analysis

Writing times for the left portion, the right portion and their total were taken as the dependent variables. All the data was analysed in the UNIVAC 1100 computer system with the help of the GENSTAT statistical package.

RESULTS

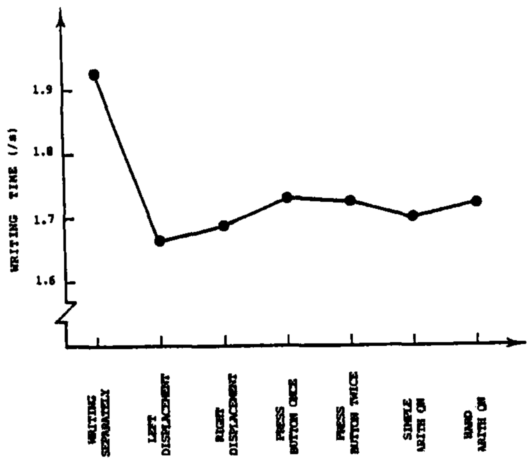
Writing times of the individual portions and the whole character under different conditions were analysed by means of ANOVA tests. Firstly, total writing times for the whole character under various writing conditions were compared and a significant main effect was found ($F(7/105) = 6.15$, $p<0.05$). Post hoc comparison using Tukey (a) Test showed that total time for writing the left and right portions separately was significantly greater than all other total writing times. Moreover, the time required for continuous writing was also significantly greater than those of the two spatial displacement tasks (Critical value = 0.218, $p<0.05$).

Figure 1 Total writing time in various writing tasks.



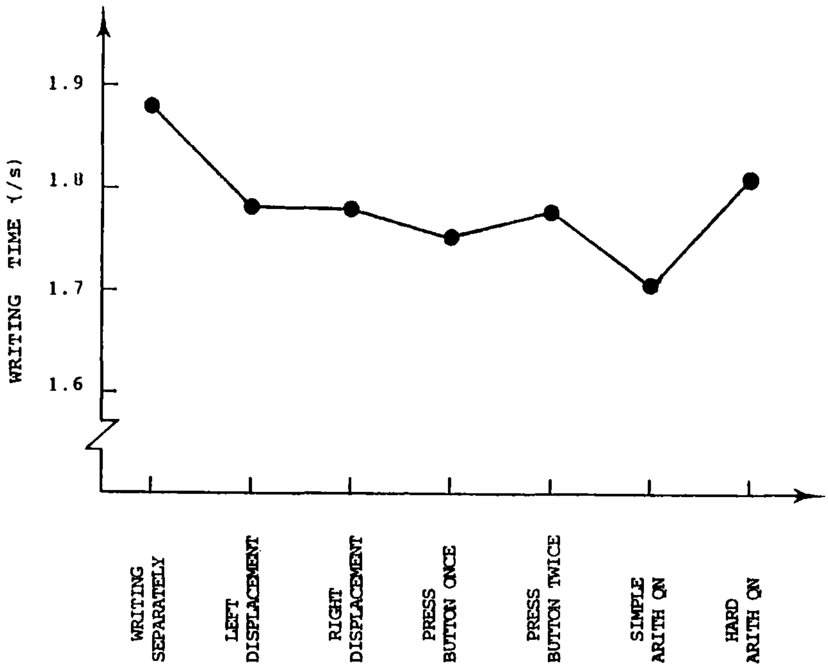
A similar one-way repeated measures ANOVA was applied to the writing times for the left portions. A significant main effect was again found (F(6/90) = 9.194, p<0.05). Post hoc comparison using Tukey (a) Test revealed a significant difference between the time required to write the left portion as an individual character and those under other task requirements (Critical value = 0.1231, p<0.05).

Figure 2 Writing time for the left portion in various writing tasks.



Though no significant difference was found amongst the writing times for writing the right portion by using one-way ANOVA (F(6/90) = 2.21, p>0.05), paired comparison using t-tests showed up differences between the writing time for the right portion as an individual character and the times for writing it under all other tasks requirements except the harder calculation task.

Figure 3 Writing time of the right portion only.

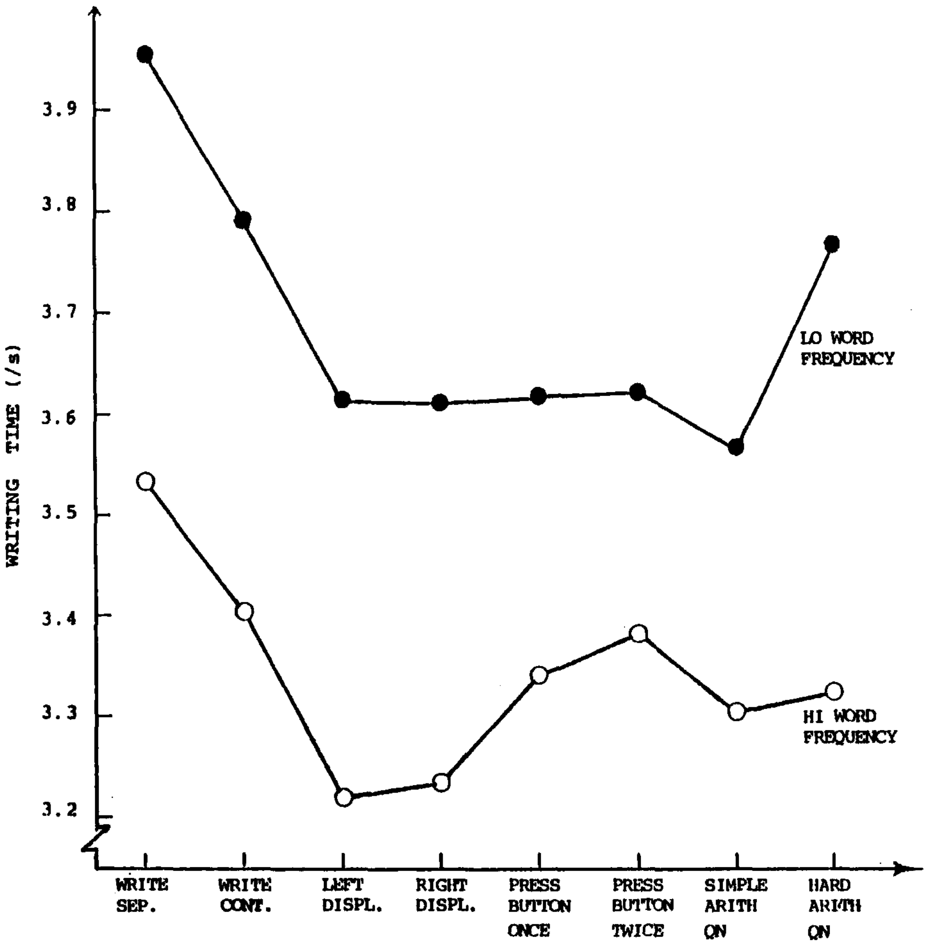


With the introduction of the frequency of the whole word as an additional within-subject factor, for a frequent word, a reduction in the writing times for the whole word ($F(1/15) = 17.56$, $p<0.05$) and the left portion was found ($F(1/15)=57.099$, $p<0.05$) but not the right portion ($F(1/13)=0.155$, $p>0.05$).

Analysis was then done by combining the baseline level (i.e., writing continuously) with the tasks in a particular type of interruption. A significant interaction was found between word frequency and tasks when the latter variable only included continuous writing and the two 'press button' tasks ($F(2/30)=3.612$, $P<0.05$) but not for other combination of tasks (e.g., writing continuously and the two spatial displacement tasks). Post hoc comparisons using Tukey (a) Test showed that the total writing time was different amongst the three tasks only under the low but not the high word frequency condition (Critical value = 0.16, $p<0.05$). Similar effects were not found for other combinations of tasks in the task variable.

Concerning the effect of the frequency of the left portion of a word, while a facilitation effect (a reduction in writing time) by high left portion frequency was found in the left portion ($F(1,15) = 88.477$, $p<0.05$), a reverse effect was found on the right portion ($F(1,15) = 175.1$, $p<0.05$).

Figure 4 Effect of word frequency on total writing time.



Finally, no interaction amongst task, frequency of the left portion and the number of strokes could be found ($F(1,15) = 3.524$, $p > 0.05$).

Different from the effect of the frequency of the left portion, a frequent right portion led to reduction in the writing times for the whole word ($F(1/15) = 29.77$, $p < 0.05$) and the right portion ($F(1/14) = 60.11$, $p < 0.05$) but not the left portion ($F(1,14) = 0.221$, $p > 0.05$). A summary of the effect of the frequencies of individual portions and whole words is given in Table 2.

Figure 5 Effect of word frequency on the writing time of the left portion.

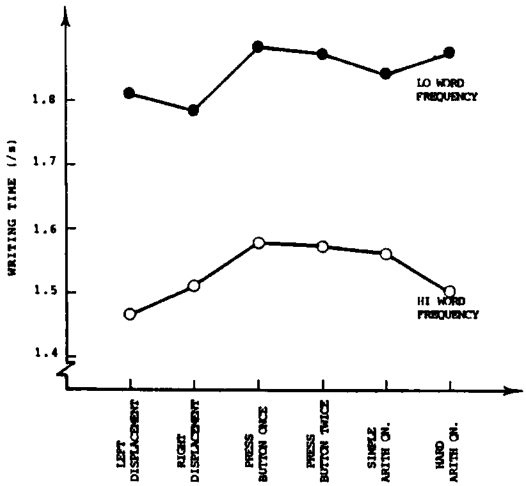


Figure 6 Effect of word frequency on the writing times of the press button tasks.

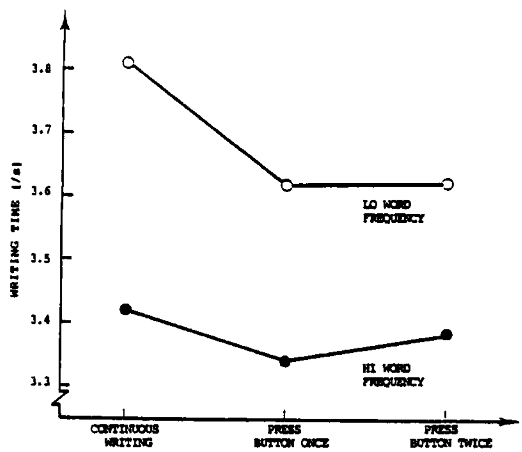


Figure 7 Effect of left portion frequency on the writing time of the left portion.

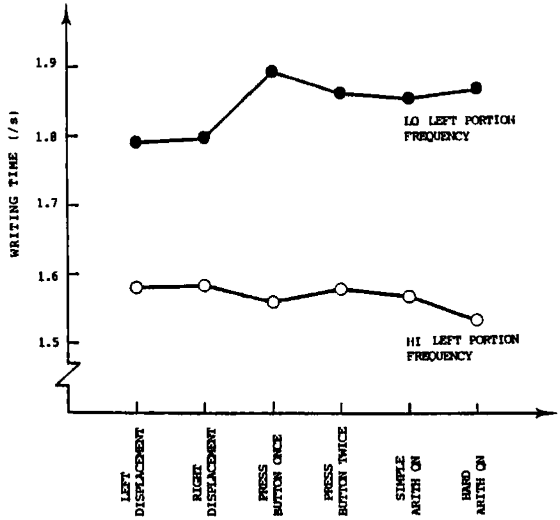


Figure 8 Effect of left portion frequency on the writing time of the right portion.

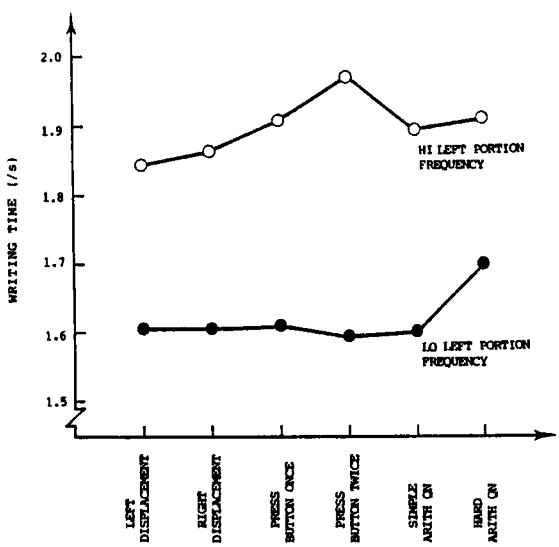


Figure 9 Effect of right portion frequency on total writing time.

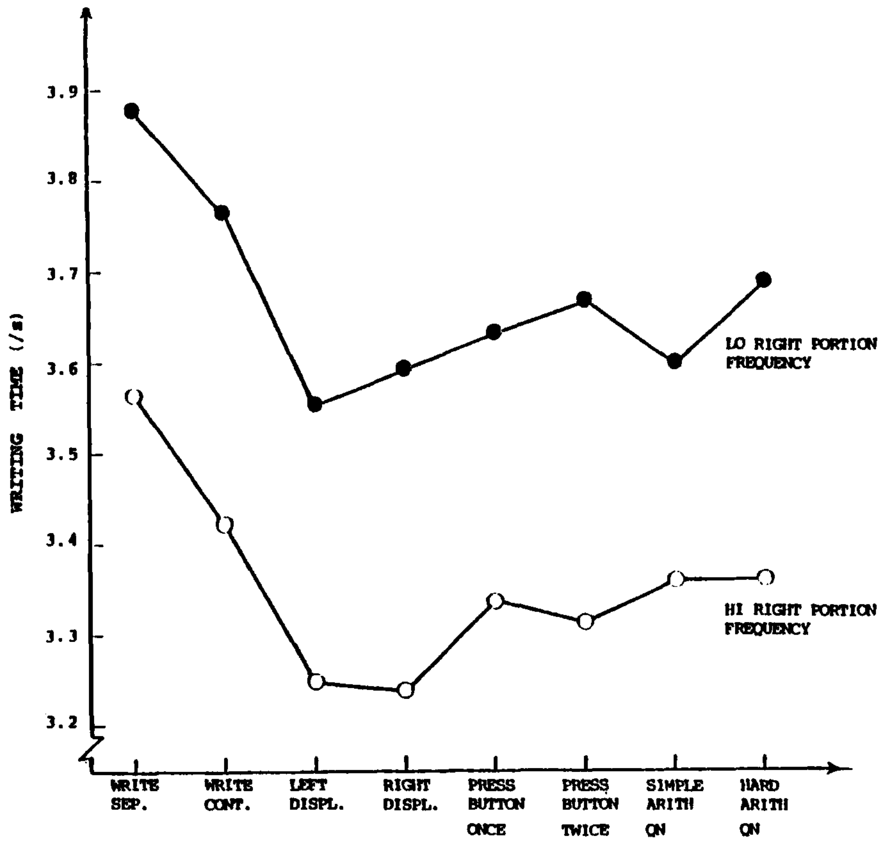


Figure 10 Effect of right portion frequency on the writing time of the right portion.

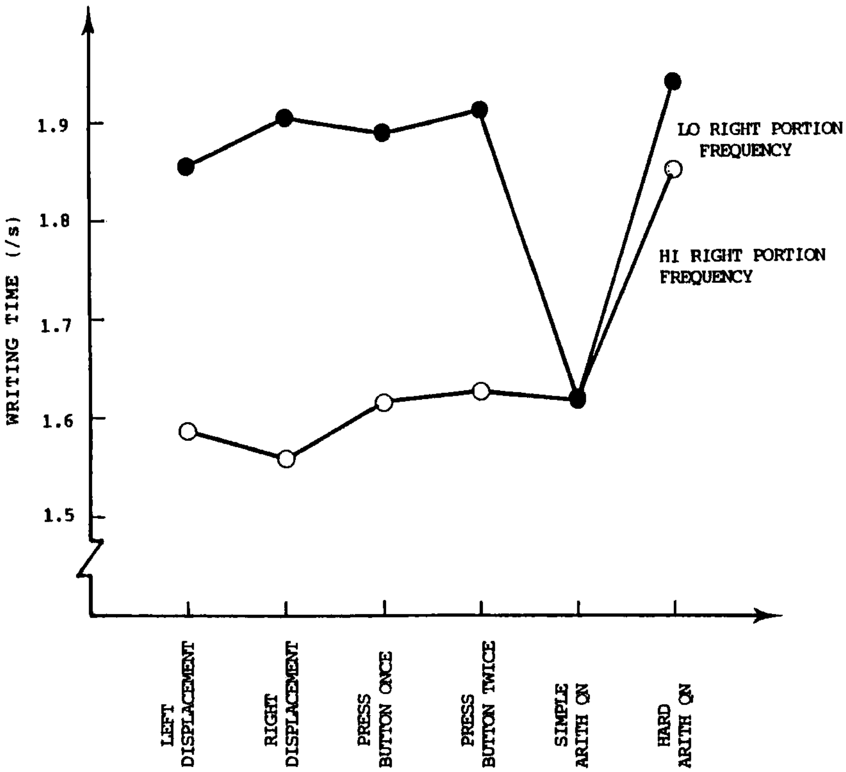


Table 2 Effect of frequency on writing time of different portions.

		Writing Time		
		Left Portion	Right Portion	Whole Word
Frequency of word	Hi Lo	Shorter Longer	No Difference	Shorter Longer
Frequency of left portion	Hi Lo	Shorter Longer	Longer Shorter	No Difference
Frequency of right portion	Hi Lo	No Difference	Shorter Longer	Shorter Longer

Once again, the interaction effect between frequency of the right portion and task was not significant ($p > 0.1$).

Lastly, as expected, writing time for words with more strokes was significantly longer than that of those with less strokes ($t = 17.74$, $p < 0.05$). However, no significant interactions were found between this variable and any of the remaining ones.

DISCUSSION

Concerning the degree to which motor movements are programmmed in advance, it was found that the total time for writing the left and the right portions separately as two individual characters was longer than that required in continuous writing. This is in line with the idea that preparation for the latter strokes is done in parallel to the execution of the earlier strokes. Therefore, when the two portions were written continuously, the search of the subprogram for the right portion and the unpacking into its constituents were done when the left portion was being executed and thereby shortening the total writing time. On the other hand, when they were written separately, the execution of the right portion could not be facilitated in such a manner and a longer total writing time was obtained.

In fact, it is quite a surprise to find a longer writing time in continuous writing in comparison to experimental conditions in which interruption tasks were introduced. Originally, it was hypothesized that such interruptions would require the subject to re-initiatise the motor program at certain levels and thereby lengthen the writing times. To account for the findings, the assumption that the preparation stage overlaps with the execution stage is again taken. It is suggested here that the duration in which the interruption task was accomplished provided an additional time interval for unpacking the right portion and thus resulted in a shorter writing time and this is particularly true in the first two types of interruption tasks. This idea is further supported by the fact that only the differences in total writing time between continuous writing and each of the two spatial displacement tasks were significant. Here, it is argued that in these two interruption tasks which are relatively simple, the subject could still allocate some resources to prepare for the execution of the right portion. Of course, this idea has to be confirmed by comparing the times taken for the right portion in continuous writing and these three interruption tasks. Unfortunately, this cannot be done in the present study due to limitations in instrumentation.

Concerning the second major question of the study, i.e., whether the execution of handwriting movements can be differentiated into different levels of processing, the following findings shed some lights on the issue. Firstly, the differences in total writing time between each of the two spatial displacement tasks and the baseline level (continuous writing) were found to be significant. Secondly, a significant interaction was found between word frequency and task when the latter variable only included the baseline line level and the two press button tasks but not for other combinations of tasks; also, post hoc comparison revealed a significantly longer baseline level only for low frequency words. Thirdly, when t-tests were used to compare writing time of the right portion when it was written as an individual word and under different writing conditions, all conditions except the complex calculation task produced significant speeding up of the writing task.

Judging from these findings, it is quite confident to say that during execution of handwriting movements, the memory representation is specified at more than one level. As mentioned above, the first finding can be accounted for by the assumption that preparation for the right portion still goes on when the subject displaced his/her hand or when s/he calculated the simple arithmetic problem. For the second finding, it is argued that preparation for the right portion still continued when the subject pressed the button; yet the more demanding nature of the task leaves not too much capacity for unpacking and the facilitation effect becomes unobservable for high frequency words as they are already processed very quickly. Using the idea of motor-program editor, as the first two types of interruption only involved a change in the motor level, it is suggested what the subject did was simply to modify the original program so as to incorporate the action of displacement or pressing the button and the new motor program was performed in a continuous manner. In other words, the motor program was adapted to the new task requirement but not interrupted in its execution as it was originally intended. For the third finding, it shows that the motor program has to be reinitiated in the complex calculation task. As shown by Baddeley and Hitch (1974), solving a simple arithmetic problem and memorising materials like a sequence of numbers would compete for the same limited short-term memory capacity. Hence, in our present case, the motor memory is likely to be interferred seriously or even erased.

Turning to the effect of frequency, generally, a high frequency of the interested unit is always associated with a shorter writing time regardless the unit is only a portion or a complete word. As the number of strokes is controlled, it can be assumed that in both levels of frequency a motor program of comparable complexity but with different degree of learning was retrieved. A frequently used word would likely facilitate the perceptual stage and the retrieval stage. Furthermore, as a high word frequency only facilitates the left portion but not the right portion, this familiarity effect actually fades out after execution commences. That is, familiar words can lead to quicker retrieval and preparation of a program and the preprogramming effect occurs only in the earliest strokes. Moreover, in Table 2, a lengthening effect was found on the writing time of the right portion by a high frequency left portion. This can be explained by the shorter writing time of the high frequency left portion which would also mean a shorter time for preparing the right portion. Finally, the effect of latter strokes on earlier strokes is still quite blurred. On one hand, as seen in Table 2, the frequency of the right portion exerts no effect on the writing time of the left portion. On the other hand, Figure 2 shows that the left portion would be written faster if the subject knew that it was followed by another portion. Therefore, the retroactive effects of the latter strokes on earlier strokes still awaits for further research.

Furthermore, the above findings give some lights on the unit of execution of writing such double-character Chinese words. As a high frequency for an individual portion is also associated with a shorter writing time, such an individual portion would constitute a unit or a subprogram of the whole motor program by itself. This is reasonable as these portions are meaningful words by themselves. When they are combined to form another meaningful word, a higher level motor program for the whole word would be formed. Therefore, it is hereby speculated that the motor program is composed of two levels structurally. On the more basic level, subprograms are prepared for each individual portion and they are then linked together to form a higher level motor program which is for the whole word. These subprograms are likely to be modified from their respective motor programs when the portions are written as individual words. Further research can be devoted to investigate the fundamental unit of such a program.

As a conclusion, the present study gives some support to the idea that advance planning is only done for the earliest strokes and preparation for the latter ones are done in parallel to the execution of the earlier ones. Secondly, different effects on writing time can be seen by introducing different types of interruption and this enables us to conclude that memory representation of the execution of handwriting movements follows a hierarchical, multi-level model of processing. Finally, evidence can also be found that while each word constitutes a motor program by itself, each component part would make up a subprogram of its own.

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ATTENTIONAL RESOURCES ALLOCATION PROCESS IN DIFFERENT MODES OF HANDWRITING CONTROL

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INTRODUCTION

In spite of the growing amount of research devoted to the investigation of handwriting performance and the underlying psychomotor mechanisms which are responsible for it (e.g., Thomassen, Keuss and van Galen, 1983), the nature of control modes in handwriting control remains unclear (Kao, Shek and Lee, 1983; Kao, Shek, Guo and Lam, 1984). There are two basic issues related to this ambiguity. First, although different modes of handwriting control can be thought of conceptually, empirical evidence for the distinction of different modes of handwriting control, especially on how various modes of handwriting control place differential demands on the various aspects of the information processing system, has been scarce, except the contribution of some recent studies (Kao, Shek and Lee, 1983; Kao, Shek, Lam and Guo, 1984). Secondly, although some cognitive models on handwriting are available (van Galen and Teulings, 1983; Stelmach and Diggles, 1982; Stelmach, 1982; Schmidt, 1982), there has been no attempt in linking different modes of handwriting control to such theoretical models.

Tracing (veridical graphic reproduction) and free-hand writing (such as signing, lettering or scribbling) as two different modes of handwriting control were identified by Kao, Shek and Lee (1983). It was found that with the employment of writing pressure as dependent variable, tracing was complexity-independent (i.e., handwriting pressure did not rise with an increase in stimulus complexity) whereas free-hand writing was complexity-dependent (i.e., writing pressure rose as task complexity increased). However, there are two limitations with this study. Firstly, the distinction between tracing and free-hand in terms of complexity dependency/independency was established on a between-subject basis only, with supporting evidence for such differentiation arising from different experiments. Secondly, although this study throws some light into the distinction between tracing and freehand writing, it is not clear whether tracing is different from other modes of handwriting control, such as copying. In fact, there is some evidence suggesting that these modes of handwriting control (tracing, copying and freehand) could be differentiated in terms of their respective cardiac and respiratory activities (Kao, Shek, Guo and Lam, 1984), suggesting that various modes of handwriting control might place different demands on the various aspects of the information processing system. However, a review of the literature shows that there have been few attempts in elucidating this problem.

On an intuitive level, tracing and copying could possibly be distinguished on several grounds. First, although the referent stimulus is externally represented in both modes (i.e., the person has to write the word with reference to some externally-represented stimulus), a substantial difference is present in terms of the spatial distance between the produced graph and the referent stimulus source. While the produced graph almost overlaps with the referent stimulus in tracing (as task requirements imply), copying, by definition, entails a spatial distance between the produced allograph and the referent stimulus. Such difference implies that the amount of eye movement and attentional shift would be greater in copying because the person has to constantly compare the produced allograph (which is distant from the source stimulus) with the stimulus source.

Secondly, the task requirements for both modes might be different. For tracing, the task requirements are more rigid and well-defined than copying because the criterion for right or wrong is apparent. Indeed, it is quite easy to check whether the produced allograph deviates from the 'boundary' of the referent stimulus. In contrast, the task requirements in copying might not be so rigid because the criterion adopted in deciding whether the task has been accomplished or not is simply the production of a graph of 'approximately' the same size and shape (therefore not really a 'veridical' production of the referent stimulus as in the case of tracing). In fact, what the person has to do is to capture and produce the essential features of the referent stimulus. Unless there is serious deviation from the referent stimulus (so that there is obvious mismatch between the produced allograph and stimulus), no great adjustment is needed.

Translating the preceding discussion to concepts related to the information processing perspective, it can be hypothesized that there might be some differences between tracing and copying in terms of their respective demands on the various aspects of the information processing system. According to van Galen and Teulings (1983), handwriting can roughly be divided into three stages, including the retrieval of a motor program from long-term memory, parameterization of the codes involved and the recruitment of the appropriate muscular units and nerves in order to execute the writing task. Similarly, Stelmach (1982) and Schmidt (1982) proposed that perception, response selection, response programming, response execution and feedback from environmental information are the basic information processing mechanisms involved in handwriting. Based on these models, it can be hypothesized that tracing, with a more rigid task demands, would place more demands on the response execution stage in order to execute the 'veridical' allograph. On the other hand, copying can be regarded as less stringent as far as these processes are concerned. Since the criterion for right or wrong is not so apparent (because the demand for veridicality is not strong and a resemblance between the produced allograph and the referent stimulus is enough for a successful execution of the writing task), there can be several possibilities in response selection. As a result, muscular demands or the recruitment of specific muscle groups under copying would not be as stringent as in tracing. If this line of reasoning is correct, it is expected that tracing would be associated with a greater amount of muscular activities (since more stringent motor requirements are anticipated which involve more muscular regulations and adjustments) and longer writing time (which is necessary for the relevant selection adjustments).

However, task requirements associated with tracing and copying might have different implications on the feedback mechanisms. Since the task is well-defined in tracing, it can be argued that the criteria involved in feedback are quite simple (because any slight deviation would signal the necessity of motor adjustment) but the amount of motor adjustments is great (because deviations are easily detected). In contrast, although task demands in copying are less stringent (because there is no apparent answer of right or wrong), the criteria involved in feedback might be more complex because a person has to spend much effort in deciding whether the produced allograph resembles the source stimulus or not. Such processes would further be complicated by the fact that the referent stimulus is not spatially identical to the produced allograph, therefore requiring more attentional shifts and eye movements during writing execution. Consequently, it can be hypothesized that although the amount of motor adjustment in copying might be small (because veridical reproduction is not required), complex central decisional mechanisms might be involved in this mode of writing.

Adopting a somewhat different but related perspective on resources utilization (Wickens, 1980; Israel, et al., 1980), it can be suggested that more resources are distributed for motor execution purposes during tracing (therefore leading to greater muscular activities during writing) whereas copying might require more resources for central decision and attentional shifts purposes.

The present experiment was designed to investigate whether tracing and copying could be differentiated according to the aforementioned theoretical considerations. Specifically, it attempted to throw some light into the nature of resources allocation in these modes of handwriting control. First, it examined whether the amount of processing capacity allocated during tracing and copying are different, and whether the degree of allocation are different for writing stimuli of different levels of frequency and complexity. In this paper, processing capacity is defined as a limited pool of multi-purpose or 'undifferentiated' resources which can be used for any purpose (Kahneman, 1973; Moray, 1967; Norman and Bobrow, 1975). According to Kahneman (1973), "tasks at different level of complexity elicit different degrees of arousal and demand different amounts of attention and effort" (p. 17), suggesting that resources allocation is a function of task demands. A dual-task experimental paradigm was employed to answer this question, a technique which has widely been employed in assessing the nature of attentional resources allocation (e.g., Isreal, et al., 1980). This technique normally involves the presentation of a secondary task during the execution of the primary task, so that processing capacity consumed by the primary task can be indicated.

However, since it has been widely found that physiological and attentional arousal affects allocation policy (e.g., Kahneman, 1973; Warburton, 1979) and that performance to the secondary task interacts with arousal (e.g., Hockey, 1973; Easterbrook, 1959), both simple and choice RT tasks were employed as secondary tasks. It was predicted that if tracing involves a higher level of arousal (and consequently leads to more intensive allocation of processing resources), response to a simple RT task during tracing would be facilitated (since there have been many studies suggesting that attentional or physiological arousal facilitates performance in simple tasks e.g., Easterbrook, 1959; Hockey, 1973) whereas performance to a choice RT task would be impaired (cf. Teichner, 1968, who suggested that high arousal leads to the impairment of response to complex secondary task).

Secondly, the present experiment attempted to understand the nature of resources allocation related to motor initiation and execution. Since the distribution of processing resources related to motor initiation and execution processes might possibly be reflected by handwriting pressure (e.g., Kao, Shek and Lee, 1983), it was hypothesized that if more processing capacity is distributed to the motor initiation and motor execution processes during tracing, handwriting pressure under tracing would be heavier than copying. In addition, since such motor execution requires the recruitment of stringent and fine muscular control, it was also expected that tracing was associated with longer writing time.

METHOD

Subjects and Design

Subjects were 32 right-handed male and female students from University of Hong Kong (age range 18-24). They had normal or corrected to normal vision and they had taken Chinese Language in the Hong Kong Certificate of Education Examination. A within-subject repeated measurement design was adopted in which each subject had to write (trace or copy) a total of 16 series of Chinese characters of different levels of frequency (2) and complexity (2), with the occurrence of a secondary task (simple or choice RT task) during the execution of the writing task. There were eight conditions related to the simple and eight conditions related to the choice RT conditions for each subject.

Apparatus and Stimuli

Subjects were seated in a comfortable chair in a sound-attentuated experimental room which was temperature and humidity controlled. A modified model of an electronic handwriting analyser (Kao, et al., 1969) was used in connection with an APPLE IIe computer for the measurement of handwriting pressure, reaction time to the secondary task and total writing time. A linear pressure transducer with a minimum of one gram force to trigger the measurement was attached under an aluminium writing plate (53 cm. × 17.5 cm.) fixed to the centre of the writing platform. To measure writing pressure, the computer sampled the point-tip pressure of the pen at a rate of one data point for every 20 msec.. A common ball-point pen was used by the subject throughout the experiment. A reaction time apparatus was placed in front of the writing platform (5 cm. × 10 cm.) which signalled red or green light. In connection with the RT apparatus, two foot-paddles were placed beneath the subjects' left and right feet for response execution purpose.

The determination of frequency for the writing stimuli was after the method suggested by Liu, Chuang and Wang (1975). Chinese characters with frequency greater than 250 or less than 10 were considered as high or low frequency characters respectively. For stimulus complexity, Chinese characters with a number of strokes less than 8 were considered as low complexity stimuli whereas characters with more than 18 strokes were regarded as high complexity stimuli. The number of characters in the stimulus series was five for the high complexity and ten for the low complexity characters. Four series of Chinese characters, with different combinations of frequency and strokes, were employed. They were repeated four times under either a tracing or a copying instruction, with the concurrent presentation of either a simple or a choice RT task, resulting a total of 16 conditions for each subject.

Procedure

The subjects were told that they had to trace and copy characters in stimulus series and they were instructed to write as fast as possible and with an accuracy as constant as possible. Prior to their experimental trials, they received several training trials in order to be familiarized with the stimuli and procedures. They were also told that during their writing task, a secondary RT task would be presented. 20 trials for simple and 20 trials for choice RT task without the involvement of the writing tasks were administered for each subject as baseline data. During the experiment proper, a secondary task was presented to the subjects during the execution of each stimulus-series between 5 to 20 seconds after the onset of the writing task. The intervals between the presentation of successive stimulus-series ranged between 3 to 7 minutes. There were 8 trials for simple and 8 trials for choice RT task conditions. Before the beginning of each condition, the subjects were informed about the nature of the secondary task. In the simple RT condition, the subjects were instructed to press the right foot paddle when the red light was presented during the writing task. In the choice RT condition, the subjects were instructed that either the red or green light would be presented and they were told to press the right-foot paddle (when the red light was on) or left-foot paddle (when the green light was on). The presentation of these two RT task conditions as well as other conditions were counter-balanced across subjects.

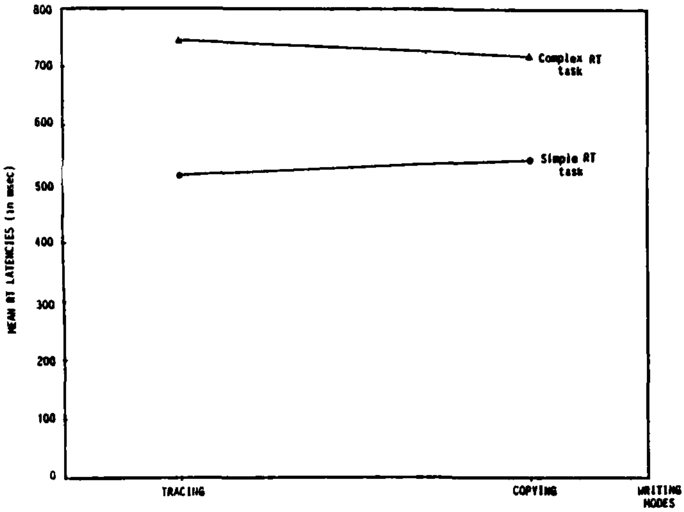
Data Analysis

Dependent variables in the experiment included reaction time to the secondary task, writing pressure and total writing time. Reaction time to the secondary task was defined as the time required to press the foot paddle in response to the probe stimulus. Apart from analysing the absolute RT data, difference scores for RT performance data were also examined. The difference score was computed by subtracting the mean baseline RT latencies by observed RT latencies (either simple or choice) over mean baseline RT latencies, which was then expressed in terms of percentage change in RT latencies. For writing pressure, mean pressure for each period was computed by dividing the sum of all observed pressure values within that writing period by the data points sampled at 20 msec. throughout the task duration. In order to further understand pressure variations in these writing tasks, writing pressure at different portions of the writing task was examined, including a) mean pressure before the onset of the probe stimulus; b) mean pressure after the response to the probe stimulus and c) mean overall pressure, excluding the period from probe stimulus onset to the execution of response to the secondary task. Finally, writing time was defined as the time required to finish writing one stimulus series, excluding the time between the onset of the probe stimulus and the execution of the response.

RESULTS

RT latencies to the probe stimulus were analysed within a four-way ANOVA (two RT conditions by two writing mode conditions by two frequency conditions by two complexity conditions). Although the analyses showed no significant effect for writing modes ($F>.10$), planned comparison using t-test showed that subjects responded faster to simple RT stimulus under the high frequency by low complexity condition during tracing ($t(31)=-2.53$, $p<.02$). Similar results were obtained using difference score data. Figure 1 shows the mean RT performance to both simple and choice RT tasks during tracing and copying.

Figure 1 Mean RT latency (in msec.) to simple or choice RT tasks during tracing or copying.



Further analyses also revealed a marginally significant effect for complexity ($F(1/31)=3.327$, $p<.085$). The mean RT performance to the secondary task under different levels of complexity by writing modes conditions are shown in Figure 2.

Figure 2 Mean RT latency (in msec.) to the probe stimulus during tracing or copying of stimulus series of low or high complexity.

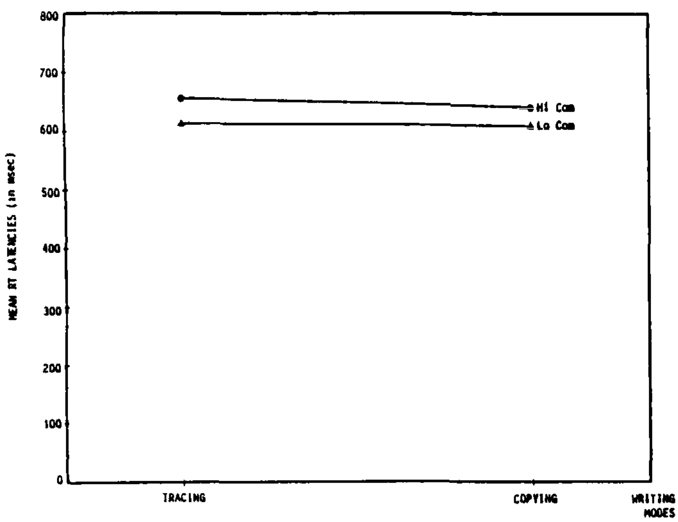


Figure 3 Frequency by writing mode interaction for pressure data after the response to the probe stimulus.

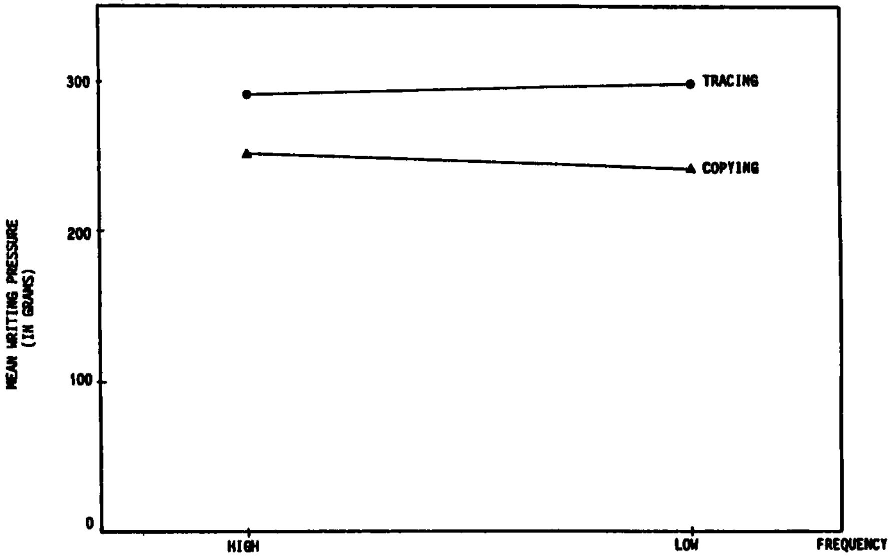


Figure 4 Mean writing pressure — a) pressure before the onset of the probe stimulus; b) pressure after the response to the probe stimulus and c) mean overall pressure under tracing and copying.

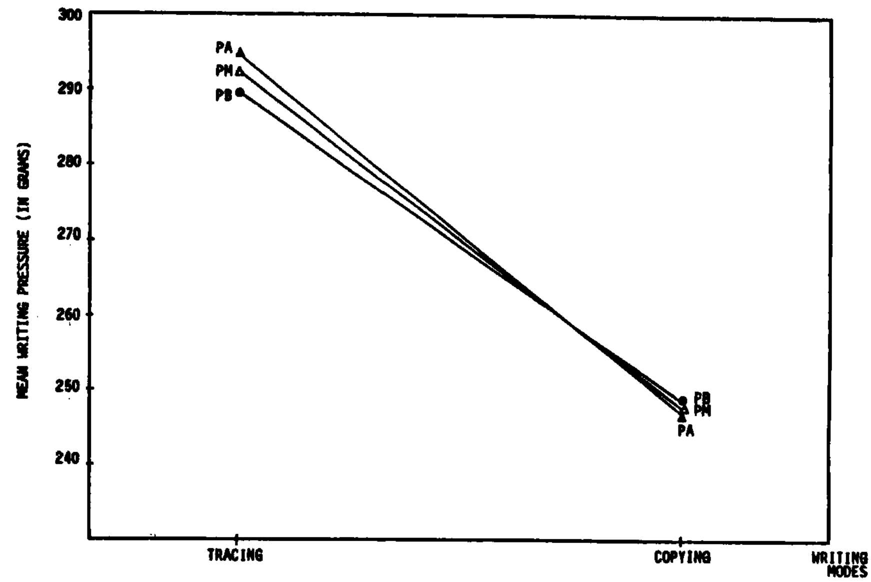


Figure 5 Mean writing pressure — a) pressure before the onset of the probe stimulus; b) pressure after the response to the probe stimulus and c) mean overall pressure involved in writing stimulus series of different levels of complexity.

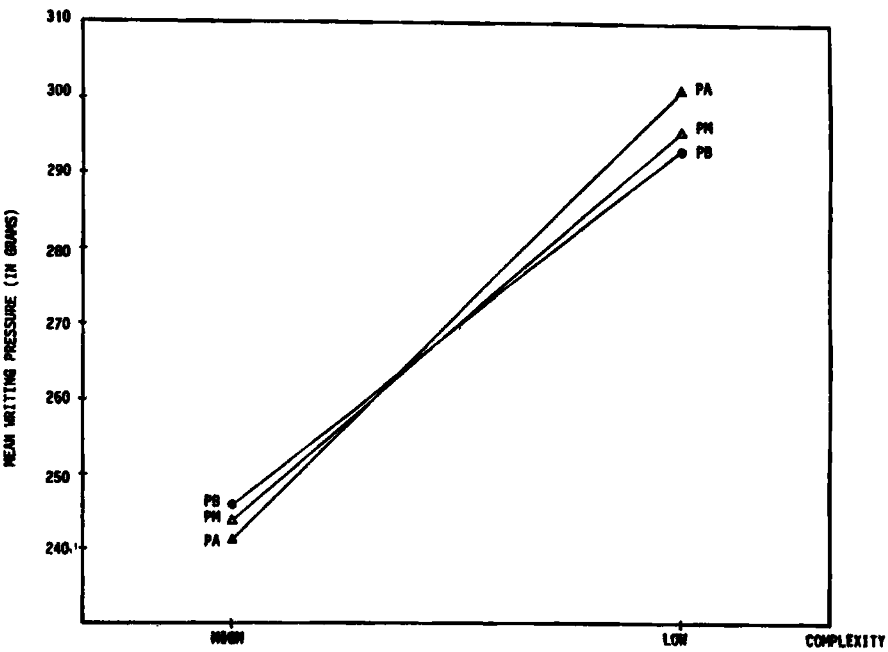


Figure 6 Frequency by writing mode interaction for writing time data.

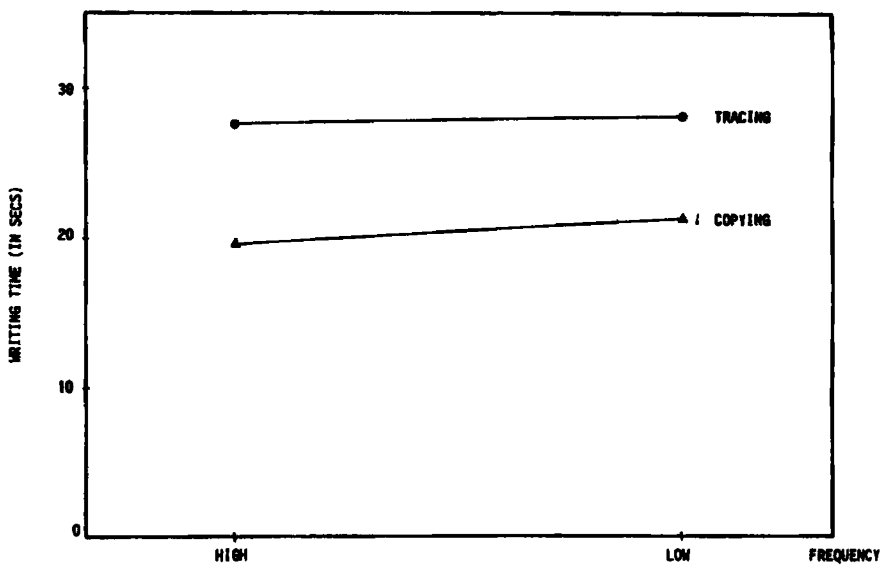


Figure 7 Frequency by complexity interaction for writing time data.

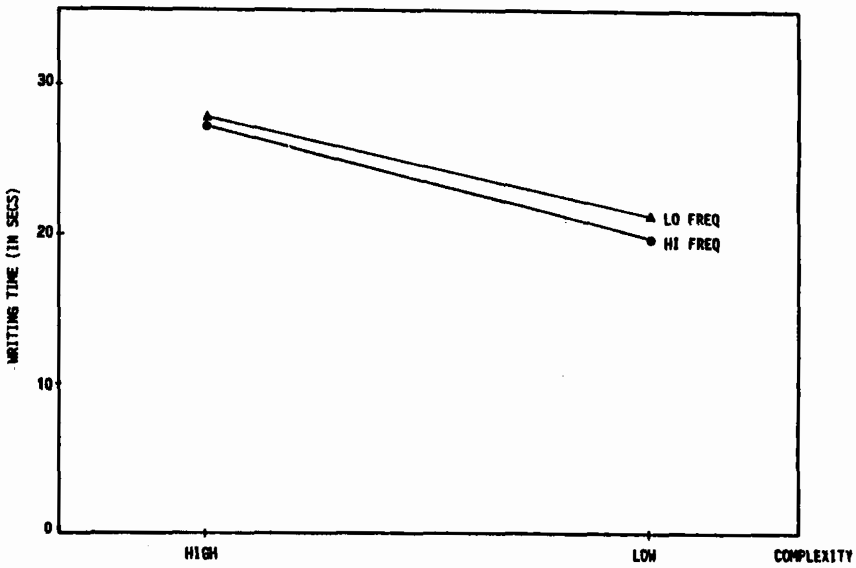
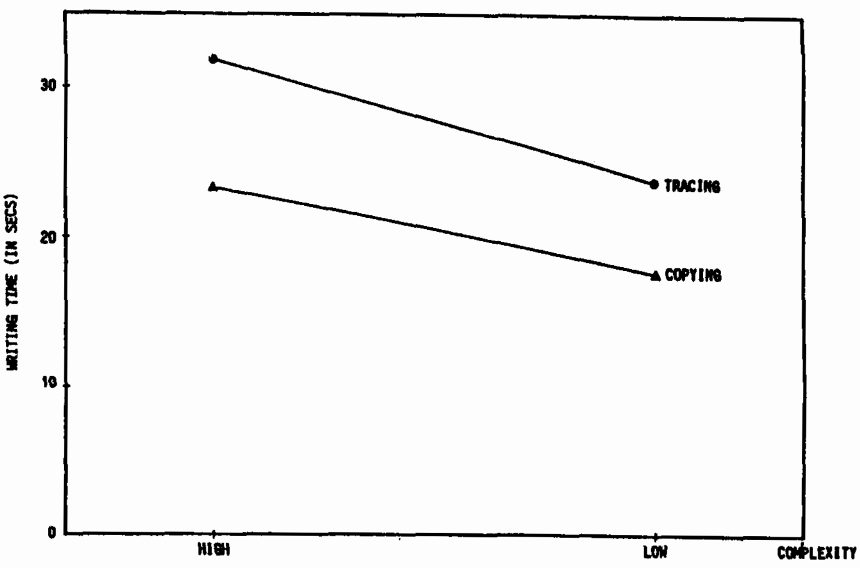


Figure 8 Complexity by writing mode interaction for writing time data.



All handwriting pressure data were analysed by a four-way ANOVA with frequency, complexity, writing modes and RT task as the main factors. For pressure data before the onset of the RT stimulus, there was a significant effect for writing modes ($F(1/31)=30.81$, $p<.001$), indicating that tracing was associated with heavier writing pressure. In addition, significant complexity effect was also found ($F(1/31)=39.78$, $p<.001$), showing that writing of more complex stimuli was associated with lighter pressure. Analyses using pressure data after the execution of the RT task similarly revealed significant effects for writing modes ($F(1/31)=30.46$, $p<.01$) and complexity ($F(1/31)=73.19$, $p<.01$) as well as an interaction between writing modes and frequency ($F(1/31)=4.85$, $p<.01$). An indication of this interaction effect may be seen in Figure 3.

Alternative analysis using mean overall pressure data (excluding the period between stimulus onset and motor response) also showed significant effects for writing mode ($F(1/31)=32.49$, $p<.01$) and complexity ($F(1/31)=59.21$, $p<.01$) as well as a writing mode × complexity × reaction time task interaction effect ($F(1/31)=4.416$, $p<.01$). The mean pressure associated with different modes and different levels of complexity for these three sets of data are graphically presented in Figures 4 and 5 respectively.

Writing time data were similarly analysed within a four-way ANOVA. The analyses showed significant main effects for writing modes ($F(3/31)=69.951$, $p<.001$), complexity ($F(1/31)=544.976$, $p<.001$) and frequency ($F(1/31)=20.582$, $p < .001$). The analyses further showed significant interaction between writing modes and frequency ($F(1/31)=9.565$, $p<.01$). Post-hoc comparison using Tukey (a) Test showed that writing characters of high frequency required less time than characters of low frequency and this relationship held under copying but not tracing. The graphical presentation of this interaction effect may be seen in Figure 6.

In addition, interaction effect for writing modes and complexity ($F(1/31)=42.241$, $p<.01$) and frequency and complexity $F(1/31)=5.592$, $p<.05$) were also obtained. Post-hoc comparison of the latter interaction effect showed that writing high frequency material was significantly faster than low frequency material at the low but not the high complexity condition ($p<.05$). The data for these interaction effects are graphically presented in Figures 7 and 8 respectively.

DISCUSSION

The results on RT latencies to the probe stimulus showed no overall significant difference between tracing and copying, although planned comparison showed that simple RT performance under the high frequency by low complexity condition was significantly faster during tracing than copying. An examination of the cell means further revealed that while simple RT performance during tracing is faster than copying, the reverse is true under the choice RT condition.

There are two possible explanations for the data obtained. The first possible explanation is in terms of the interaction effect between attentional arousal and resources allocation. Since the engagement in different forms of writing activities would constitute some sort of 'momentary effort' for the subject, this would lead to arousal and allocation of more processing capacity to the organism for actual and anticipated demands (Kahneman, 1973, p. 25, p. 48-49). Assuming that the stringent requirements related to motor initiation and motor execution under tracing lead to more arousal than copying (a speculation in agreement with the pressure data), such effect would affect the allocation policy (possibly attentional narrowing, Kahneman, 1973; Hockey, 1979), which in turn interacts with task demands in affecting performance. Such changes explain why while simple RT performance is faster during tracing than copying, the reverse is true for the choice RT condition. In addition, since task demands under the high frequency by low complexity condition is the simplest, additional capacity brought forth by arousal can easily be used for the execution of the simple secondary task. For other conditions with the occurrence of the simple RT task, more stringent task demands might offset the additional resources allocated during tracing. However, although there are some trends in the data which partially support this possibility, the insignificant overall results suggested that other factors might be in operation. One possibility in that although arousal might be higher in tracing (with more processing capacity allocated for motor initiation and execution purposes), a considerable amount of processing capacity is also allocated during copying for other purposes, possibly contributing to the insignificant results obtained.

The second possiblity is related to the hypothesis that the total amount of processing capacity allocated to tracing and copying are relatively the same. However, even if this explanation stands, it is suggested that resources allocated in these two modes might be used for different purposes (see below). In addition, this explanation cannot adequately accomodate the finding that simple RT performance at the high frequency by low complexity condition is faster during tracing than copying.

The marginally significant effect for complexity showed that RT latencies to the probe stimulus were lengthened when writing stimulus series of increasing complexity. This finding is in line with the hypothesis that the more complex the stimulus series, more resources are allocated to the actual or anticipated demands related to the execution of the writing task. Such changes in the allocation policy would then leave little resources to respond to the secondary task, leading to the lengthening of RT latencies observed. Since the results obtained are marginally significant, further experimentation employing more levels of complexity would surely illuminate the nature of resources allocation in writing stimulus series of different levels of complexity and the effects of different task demands.

For writing-pressure data, an interesting writing mode effect was obtained. The data show that writing pressure is heavier in tracing than copying, and this finding is consistent for pressure data before the onset of the probe stimulus, pressure data after the response to the probe stimulus and mean overall pressure data. The increase in the amount of handwriting pressure under tracing might possibly reflect the stringent and specific motor requirements related to this mode of handwriting control and this finding is in line with the hypothesis that the amount of muscular activities in tracing is greater than copying as a result of the differential demands on the motor initiation and motor execution processes. This speculation is also in agreement with Stelmach and Diggles's (1982) idea that "coordinated movement would require a smoothing or tuning function to choose and fit appropriate units of muscles to approximate the intended movement" (p. 94). Since tracing can be regarded as a task requiring a high level of co-ordinated movements, such requirements would be translated into relevant muscular demands, which in turn are reflected in the pressure data.

The discrepancy between RT latencies and pressure data deserve some further considerations here. It was found that while writing pressure is higher during tracing than copying, there is no difference in the subjects' RT responses to the probe stimulus during execution of these writing tasks. Such findings pose a very interesting question of why pressure data differences are not reflected by the RT performance data. One obvious explanation for this observation may be that while tracing draws more resources for motor initiation and motor execution purposes (therefore leading to difference between these two modes on pressure data), copying might require more processing capacity used for purposes other than motor processes which are not so relevantly be reflected by pressure index. Since the produced allograph is spatially distant from the referent source stimulus and the criteria involved in deciding whether the production is right or wrong are not so clearly defined in copying, additional processing capacity might be required by the subject an evaluation of the produced allograph. As has been highlighted in previous sections, such processes might also be accompanied by constant attentional shifts and eye movements. If this interpretation stands, the results obviously suggest that the direction of attentional resources allocation in tracing and copying are different, at least as far as motor initiation and motor execution processes are concerned. According to Gopher and Sanders (1984), two major types of resources, one related to perceptual and the other to motor demands, are identified. With reference to this conceptualization, it can be speculated that while more resources are allocated to motor processes during tracing, copying might require more resources distributed for perceptual purposes. While the first part of this speculation is supported by our pressure data, it is not clear yet these two modes of handwriting control are different in terms of their respective demands on perceptual resources.

As for the significant complexity effect, it was observed that tracing high complexity characters was associated with lower pressure, a finding which is not in line with the complexity-independency hypothesis (Kao, Shek and Lee, 1983), in which it was hypothesized that pressure did not increase with an increase in stimulus complexity. Although it is still not completely clear why handwriting pressure decreased as stimulus complexity increased, an 'initial adjustment' hypothesis is put forth to interpret the data. Assuming that a certain amount of muscular adjustment and effort are required for writing each character (Stelmach and Diggles, 1982) and that such motor adjustments and effort would stabilize after certain initial adjustments. If the character under writing is of high complexity, such initial motor adjustment would benefit the writing of the later portion of the character (after the initial motor adjustment effect has been stabilized), resulting in lower mean pressure. In contrast, in writing a character of low complexity, initial motor adjustment cannot benefit the writing of that particular character because adjustments might still take place throughout the writing of the character, which results in a higher overall mean pressure. Of course, further empirical evidence is necessary in order to substantiate the validity of this interpretation.

The results on writing time show that tracing requires more writing time than copying in executing identical writing tasks. It is suggested that such increase in writing time might reflect greater effort and muscular adjustments involved in this mode of handwriting control. This hypothesis is in line with the pressure data, where it was found that heavier writing pressure was associated with tracing. In addition, it was found that writing time varied with frequency, with the data showing that shorter writing time was required to write stimulus series of higher frequency. The data suggested that apart from facilitating perception of the stimuli, stimuli with high frequency would also facilitate related motor processes. However, analysis of the breakdown of the interaction showed that such facilitation effect was destroyed in tracing, implying that frequency does not necessarily facilitate all modes of handwriting control and specific motor requirements might lead to different effects. In addition, when writing stimulus series of high complexity, facilitation effect of high frequency also disappeared (i.e., whether the frequency is high or low does not have any different effect on writing stimulus series of high complexity). Such findings obviously suggested that there are certain limits of the facilitation effect of high stimulus frequency and such data can pave ways for generation of new hypotheses for future investigation.

In conclusion, the present experiment gives rise to some interesting data on the distinction between tracing and copying. While tracing and copying cannot be differentiated in terms of the subjects' response latencies to the probe stimulus during the writing task, these two modes were associated with different levels of writing pressure and different durations of writing time. Although the overall results for RT performance to the secondary task are non-significant, there are partial indications that attentional arousal was higher during tracing. For pressure data, a higher level of pressure observed under tracing suggested that more stringent demands on the motor execution and motor initiation processes are in operation. The discrepancy found between RT and pressure data further suggested that the nature of resources allocation during tracing and copying are different, at least with more resources allocated to the motor-related processes under tracing. The data are also not in line with the complexity-independency hypothesis and it is suggested that this might be attributable to initial motor adjustment effect. The data obtained obviously pave ways for further experimentation. For example, concurrent recordings of physiological activities (such as EMG) would give further illumination on what sort of muscular activities are involved in different modes of writing control. Similarly, further evidence is needed in elucidating whether more perceptual resources are utilized under copying than tracing.

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INVARIANTS IN HANDWRITING: THE INFORMATION CONTAINED IN A MOTOR PROGRAM

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INTRODUCTION

The notion of abstract motor programs for the performance of fast and complex motor patterns such as handwriting, is well established (e.g., Keele, 1981). Bernstein (1967), Klapp (1977), Lashley (1951), Morasso (1981), and Russell (1976) have argued that motor programs are unlikely to be represented in long-term motor memory in terms of concrete muscle contractions or joint flexions. But what type of movement information is in fact represented? It could be primarily spatial information as the latter authors suggest, or temporal information (e.g., Denier van der Gon and Thuring, 1965; Viviani and Terzuolo, 1982; Wing, 1978). This paper presents a method for searching for more and more invariant movement characteristics and it applies this method to the spatial and temporal characteristics of a handwriting pattern. The search for invariants is of interest because the most invariant movement characteristic under differing execution conditions should be closely related to the movement information stored in long-term motor memory.

According to the literature on motor programs, temporal as well as spatial characteristics have been claimed to be strikingly invariant, but the degrees of their invariance have never been compared. It has been shown, for example, that movement patterns performed by the same subject at different size and speed, or with different limbs (involving varying sets of muscles) show highly invariant spatial (Lyons, 1964; Merton, 1972; Smyth & Wing, 1984; Stockholm, 1979) and temporal characteristics (Cutting & Kozlowski, 1977; Denier van der Gon & Thuring, 1965; Katz, 1951; Keele & Summers, 1976; Shapiro, Zernicke, Gregor, & Diestel, 1981; Tuller, Kelso, & Harris, 1982; Viviani & Terzuolo, 1980; Wing, 1978).

Comparing Movement Characteristics

In order to compare the degrees of invariance of spatial and temporal characteristics, one has to derive an equation that relates both characteristics.

Equation of Movement Yields Four Characteristics

Handwriting movements can be adequately described in terms of the horizontal and the vertical coordinate of the pen position as a function of time. An equation of movement (e.g., Bernstein, 1967; Wing, 1978) relates the exerted muscle force to the sum of the inertial (accelerative) forces and several friction forces along the horizontal and along the vertical axis. The friction forces are small as compared to the accelerative forces and may therefore be neglected (Denier van der Gon and Thuring, 1965). The accelerative force may then be set proportional to the muscle force. Furthermore, we may restrict our study to the vertical component of the writing movements since this component appears to be the more sensitive one to variations in timing of the force bursts (Vredenbregt, Koster, & Kirchhof, 1969).

Starting from the simplified equation of movement (i.e., in the vertical direction and without friction forces) one can express the vertical size of a stroke in terms of stroke duration and peak force during the stroke (See Appendix A). But these data are not sufficient to provide a full description. Also the shape of the force curve over time has an effect. The force-efficiency factor *E* expresses this effect: i.e., the stroke size produced while peak-force and stroke duration are given. In Appendix A it is shown that the vertical size (*s*) of a stroke is proportional to the square of the duration of a stroke (*T***2), proportional to the peak force (which is in turn proportional to the peak acceleration *A*), and, finally, proportional to the force-efficiency factor of the force-time pattern (*E*):

$$s = E * A * T**2 \qquad (1)$$

Therefore, we shall define the following characteristics of a specimen of handwriting: the *spatial characteristic* (i.e., the sequence of vertical stroke sizes of a writing pattern), and the *temporal characteristic* (i.e., the squence of *squared* stroke durations). But if we wish to compare the spatial and temporal characteristics we should also consider the force-level and force-efficiency characteristics. Of course only three of these characteristics can be independent. In principle, each of them could constitute the primary information in motor memory but the spatial and the temporal characteristics evidently seem to be the most promising ones. So we define the *force-level characteristic* by the sequence of peak accelerations of the strokes of a writing pattern and the *force-efficiency characteristic* by the sequence of force efficiencies. In fact, we are not interested in absolute measures (e.g., size, which is rather arbitrary), but in relative measures (e.g., the size ratios). Therefore the sequences have to be normalized first.

In order to compare the degree of invariance of these four characteristics we shall introduce three criteria. The need for developing such criteria, which are to be based on the statistical relations between duration, distance travelled and applied force, has already been stressed by Wing (1978, p. 166).

Three Criteria to Identify the Most Invariant Characteristic

If the values of the four characteristics are indeed related as described by Equation 1, one can derive the following three criteria to decide whether the temporal, the spatial, or perhaps one of the other two characteristics (force level or force efficiency) are most invariant over replications of a specific handwriting pattern.

The first criterion employs the *signal-to-noise amplitude ratio* of a characteristic (as known in signal analysis; See Footnote 1). The 'signal' is the average characteristic while its 'noise' comprises the fluctuations between the average and a specific replication. Those movement characteristics that are primarily stored in a specific motor program should possess relatively little 'noise,' or a high signal-to-noise amplitude ratio.

The second criterion employs *inter-characteristic correlation* coefficients. Let us suppose that the temporal characteristic constitutes the basic information from which the motor system computes the force and the force-efficiency characteristics (while the spatial one is simply following from straightforward mechanics). Longer-duration strokes and higher force levels normally go together (e.g., Thomassen & Teulings, 1985). So we would expect that random fluctuations of the temporal characteristic (relative to the memory representation) are positively correlated with those of the force characteristic. On the other hand, let us suppose that it is the spatial characteristic that constitutes the basic information from which the motor system computes the movement's further characteristics. Following Equation 1 many combinations of values of the temporal, force, and force-efficiency characteristics, which all realize the intended spatial goal, could be chosen by the motor system. If, for instance, the motor system happened to adjust the duration of a stroke greater than its average in that specific context, it could still obtain the intended stroke size by selecting a smaller force or force efficiency than their averages in that specific context. Under the latter condition correlations between temporal and force characteristics might become negative. Thus, one can discriminate between the two hypotheses by checking whether the correlation between the temporal and the force characteristics are significantly negative or positive.

The third criterion is concerned with the robustness of a characteristic (expressed by the *inter-condition correlation*) across various instructed global transformations of the movement pattern, such as writing at a different size or speed, or with respect to some arbitrary manipulation of the writing conditions such as writing without visual feedback, or writing on a low-friction surface while reducing proprioceptive feedback. We assume that the same centrally stored abstract motor program is in operation for each of these conditions (e.g., Stelmach & Teulings, 1983; Van Galen, 1980), whereas the less abstract parameters are adapted ad hoc during the writing because they pertain to the frequently varying writing circumstances. So the characteristic that shows the highest correlation across writing conditions within a subject is most likely to constitute the primary movement information in long-term motor memory.

EXPERIMENT

In this experiment the subjects repeatedly perform a specific writing pattern in a normal way as well as in three "unusual" conditions (writing larger, writing slower, and writing on a low-friction surface without visual feedback). These conditions are such that it may be expected that the same abstract motor program in long-term motor memory is involved. The recorded writing movements are subdivided into separate strokes and the normalized spatial, temporal, force, and force-efficiency characteristics introduced above, are calculated. Finally, each of the three criteria discussed (signal-to-noise ratio, inter-characteristic correlation, and inter-condition correlation) are applied in order to decide whether the spatial or the temporal characteristic is more invariant across replications and conditions.

Method

Subjects

Four male, naive right-handed subjects (psychology students and staff members, aged 23 to 31) participated in the experiment. They satisfied the requirement of producing the experimental writing pattern (*mehelmen*) cursively and without pen lifts. A fifth subject did not fulfill this requirement.

Materials

The positions of the pen tip during the writing movements were recorded by a computer-controlled digitizer (Vector General Data Tablet DT1) with an RMS error less than 0.2 mm. at a sampling rate of 200 Hz. A sheet of paper with a horizontal writing base line was attached onto the writing area. The subject wrote on another sheet of paper that covered the first one but the line was still visible. On every trial the top sheet was shifted upwards such that writing position and orientation could be maintained. In one condition the subjects wrote on a low-friction writing surface consisting of an overhead transparency sheet while the writing hand remained resting on a normal sheet of paper. In this condition, moreover, the ball-point tip did not leave a trace behind, so that both proprioceptive and visual feedback were reduced.

Procedure

In order to initiate a trial the subject pressed the pen on the writing area and a buzzer sounded. The subject was instructed to keep the pen on the paper in a relaxed way until a second buzzer sounded after a random interval between 1000 and 3000 ms. in order to reduce the probability of artifacts due to anticipation. The subjects were instructed to wait for the second buzzer and then to write the pseudoword *mehelmen* cursively at a comfortable speed and without lifting the pen during the entire recording period of 4 s. The trace of the recorded movement was shown on a graphical display. If subject or experimenter were not satisfied the trial could be repeated, but once a trial had been accepted it was definitely adopted in the analysis. Each subject performed one series of 16 replications under each of the four different conditions. First they performed the *normal condition*. Then they performed a series under each of the following conditions in random order: write about twice as large as normal (*write-large condition*), write about twice as slow as normal (*write-slow condition*), and write normally on a low-friction surface (reducing proprioceptive feedback and visual feedback; *smooth-surface condition*). It should be mentioned that the recording period and sampling rate in the write-slow condition were adapted; they were 6 s and 125 Hz, respectively.

Analysis

The writing pattern was divided into separate up and down strokes. Since for the present purpose we are interested in steady-state handwriting, the first four and the last five strokes were omitted. Therefore, the writing pattern *mehelmen* contains $29 - 9 = 20$ target strokes. The strokes were identified automatically as follows: First, vertical velocity was determined from the sampled vertical position by differentiating and low-pass filtering (sinusoid transition band 8 to 24 Hz; see Teulings & Maarse, 1984). Time marks were calculated of those moments on which the vertical-velocity curve crossed the zero-velocity level (interpolating between samples). The height (or vertical size) of a stroke is the absolute difference in vertical position between two successive time marks. As defined in the introduction, the *spatial characteristic* is the normalized sequence of heights of the 20 successive strokes. The duration of a stroke is the interval between two successive time marks. The *temporal characteristic* is the normalized sequence of squared durations of the 20 successive strokes. The peak force of a stroke was estimated from the absolute maximum of the acceleration curve between two successive time marks. So the *force characteristic* is the normalized sequence of peak forces of the 20 strokes. The force efficiency per stroke can be determined from size, duration and peak-force values using Equation 1. The pattern of force efficiencies of the 20 strokes forms the *force-efficiency characteristic*.

Results

Below, each of the three characteristics will give an answer as to whether the spatial or the temporal characteristic is the more invariant one.

The *signal-to-noise amplitude ratios* of each characteristic were averaged over subjects and conditions and yielded the following data: spatial 5.5; temporal 2.7; force 1.3; and force efficiency 0.9. So the spatial characteristic reaches the highest signal-to-noise ratio of all characteristics (sign test, N=16 subjects × conditions, x=0, p<.001). This is taken to support the hypothesis that the spatial characteristic, rather than the temporal characteristic, constitutes the more important information stored in the motor program. The force-efficiency characteristic apparently contains very little information so that it was decided to leave this characteristic out of our further comparisons.

The *inter-characteristic correlation* (between each pair out of the spatial, temporal and force characteristics) has been determined for each of the 20 strokes of the writing pattern. The correlations between the spatial and temporal characteristics and between the spatial and force characteristics are predominantly positive (sign test, N = 320 strokes × subjects × conditions, x=240 and 309, respectively, z>8., p<.001). However, more important is the significantly negative correlation between the temporal and force characteristics (sign test, N=320, x=52, z>12, p<.001). Apparently, duration fluctuations and force fluctuations are traded off against one another, governed by a higher-order control characteristic. This is again taken as evidence for the hypothesis that the spatial characteristic forms the primary information from which temporal and force characteristics are derived by the motor system.

On behalf of the *inter-condition correlation* (between the normal condition and each of the other three conditions) the average 20-stroke pattern of each characteristic has been calculated per condition and per subject. Correlations were determined between a characteristic's pattern under the normal condition and under each of the three other conditions. The inter-condition correlations of the spatial characteristic were on the average 0.99, those of the temporal characteristic were 0.95, and those of the force characteristic were 0.79. So the spatial characteristic reaches the highest correlations (sign test, N=11, x=1, p<.05). Apparently, of the three characteristics the spatial characteristic is the most robust one under execution variations that are arbitrary and supposedly irrelevant as to the retrieved motor program. This is again interpreted as supporting the hypothesis that the spatial characteristic is more likely to belong to the information primarily stored in the motor program than the temporal or the force characteristic.

Discussion

The present experiment demonstrated a method for determining whether the spatial or the temporal characteristic of a handwriting pattern is more invariant over replications under normal conditions as well as under voluntary transformations, or extraordinary execution conditions. The more invariant characteristic is assumed to be more closely related to the movement information stored in long-term motor memory. By means of an equation of movement we defined the spatial and the temporal characteristics and their relationship. The equation of movement required that two other characteristics should be considered as well: the force-level characteristic and the force-efficiency characteristic. At an early stage, however, the latter characteristic appeared to contain virtually no movement information. The degree of invariance of the other characteristics could be compared by means of three criteria. Applying these three criteria, we observed that the spatial characteristic showed the highest signal-to-noise ratio; that its component factors, viz., the temporal and the force characteristics, are negatively correlated; and that the spatial characteristic showed the highest inter-condition correlation. Since apparently the spatial characteristic is the more invariant one it is concluded that this characteristic is very closely related to the movement information stored in a handwriting motor program.

Disproof of Alternative Explanations

The negative correlation between time and force could have been introduced if the subjects would have inserted hard-to-detect pauses or hesitations during their writing, so that in one stroke the force level would decrease and the duration would increase. However, the present result is also found by Newell, Carlton and Carlton (1982) in single-phasic, ballistic arm movements were such hesitations are less likely.

The negative correlation between duration and force level cannot be explained either by a feedback mechanism which would adjust, in a quasi-simultaneous fashion, stroke duration such that the intended stroke size is realized (as might occur in slower drawing movements). This is unlikely, however, because we obtain similar results in the low-friction and reduced-feedback condition as in the normal condition.

One might suggest that the negative correlation between time and force is caused by the pen-paper friction (or the static friction; MacDonald, 1966) which inhibits the start of the actual pen movement and facilitates the stop while the pen attains a higher acceleration level. Since pen pressure appears to be modulated also very characteristically during writing (Kao, 1983; Lin, Herbst & Anthony, 1979; Tripp, Fluckiger, & Weinberg, 1957) this effect is probably even hard to isolate. However, evidence to rule out this explanation is again provided by the results under the low-friction condition because they were similar to the ones under the normal condition.

At first glance it is reasonable that the temporal characteristic is often argued to be part of the movement program. For instance, in gross arm movements it is duration that is adjusted to achieve a specific movement distance. (Wadman, Denier van der Gon, Geuze, & Mol, 1979). However, Thomassen and Teulings (1985) argued that in gross movements, it is only duration that can be adjusted because force adjustment tends to level off. In contrast, when small handwriting movements are generated, both duration and force level appear to be adjusted to approximately the same extent which, in fact, supports our notion of the higher-level control by the spatial characteristic.

Motor Learning

It is obvious that only those features that describe the desired outcome economically and conclusively, will be stored in a motor program. Handwriting is a typical graphic skill from the first time of writing instruction onwards and therefore the spatial characteristic defined and employed in the present paper is likely to be closely related to the more fundamental movement information stored in the handwriting motor program. On the other hand, in spatio-temporal skills where storing temporal information is essential (e.g., tapping, dancing, conducting an orchestra) one would expect that the temporal characteristic is more invariant. In the latter class of skills, it appears, moreover, that only timing patterns with simple interval ratios can be stored in motor memory (Povel, 1981), whereas the timing patterns in handwriting do not show any tendency towards restrictions to such simple interval ratios. A practical conclusion of the present research might be that in efficient writing instruction the pupil should be trained to generate mentally the spatial goal positions (Pantina, 1957) and to produce smooth strokes connecting these goals (Søvik, & Teulings, 1983).

Invariant Temporal Characteristics Induced by Lower-order Mechanisms

Although the temporal characteristic probably does not constitute the primary source of movement information in the motor program, it actually serves as the most convenient and forgery-proof procedure for signature verification algorithms (e.g., Crane & Ostrem, 1983; Lin, Herbst & Anthony, 1979). It cannot be denied that several spatial aspects appear to be highly discriminative between subjects (Maarse, Schomaker, & Teulings, 1985). One explanation for the fact that the temporal characteristic still displays such a high degree of invariance might be that the motor system is well-trained in producing the smoothest trace that satisfies the desired spatial outcome. A smooth trace will contain in general various curvatures in clockwise or counterclockwise direction. If we suppose that in a system of two independent antagonistic muscle groups the refractory period of a muscle group is about 200 ms., one can argue that the time needed to describe one circle is also at least 200 ms. In general, the amount of time needed to describe a part of a circle is more or less proportional to its arc length (in degrees) which implies an approximately constant ratio between velocity and curve radius (Viviani & Terzuolo, 1980; Hollerbach, 1981) or at least may show some definite relation between velocity and radius (Laquaniti, Terzuolo, & Viviani, 1983; Thomassen & Teulings, 1985). Because of the invariant spatial structure, the temporal characteristic in handwriting movements will in practice be highly invariant also, but it can never be more invariant than the spatial characteristic because it is derived from it.

Even in timed tapping tasks one might doubt whether the task is stored in terms of a temporal characteristic. For example, Keele and Summers (1976) trained two groups of subjects to reproduce various keying sequences according to two different interval patterns (either repetitively 500-100-100 ms. or 500-500-100 ms.) but they noted that during the actual reproduction the ratio between the long and the short interval was not 5 to 1 but rather 2 to 1, which could be evidence of the storage limitations of a timing sequence (cf., Povel, 1981). However, during the next session the subjects were told to reproduce the keying sequence as rapidly as possible while timing structure was no longer important. They found that some time structure was retained and concluded that timing is an integral part of the motor program. They restricted their conclusion, however, by noting that this is apparently true only for certain interval patterns, while for other patterns the trained time structure deteriorates rapidly, e.g., for those patterns without a simple four-beat interval pattern. Close inspection of the final-session interval data shows, however, that the temporal structure of each deteriorated pattern tends to become identical. In fact, this is in favour of the interpretation that the retained temporal structure is not primarily stored in a motor program, but merely the consequence of the hierarchical structure of the movement pattern induced by the periodicity of the interval pattern.

The above examples intend to demonstrate that various lower-order mechanisms may bring about systematic timing properties without providing evidence, however, that a temporal characteristic is itself stored in the abstract motor program of a handwriting pattern.

FOOTNOTES

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1. The signal-to-noise amplitude ratio (i.e., the square root of the signal-to-noise energy ratio) can be estimated as follows: First we calculate the variance of the mean *varxmean* (i.e., the variance across the 20 strokes of the means over replications) and the mean variance *varx* (i.e., the mean over strokes of the variances across the 16 replications). The signal-to-noise amplitude ratio is defined as the square root of the quotient of the variances of the signal (which is estimated by varxmean

* n/(n−1) − varx/(n−1)) and of the noise (which is estimated by (varx − varxmean) * n/(n−1)) where *n* is the number of replications.

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APPENDIX A

Equation of Movement

The net vertical distance (s), travelled by the pen tip during a stroke, i.e., between two moments of time at which the vertical velocity is zero (Say at $t = 0$ and $t = T$, respectively), can be expressed in terms of the acceleration as a function of time ($a(t)$) as follows:

$$s = \text{Integral}[0,T]dt' \, [\text{Integral}[0,t']dt \; a(t)] \qquad \text{(A1)}$$

The acceleration curve a(t) can be rewritten in terms of amplitude A, duration T, and time function a' having amplitude 1 and duration 1, as follows:

$$a(t) = a'(t/T) * A \qquad \text{(A2)}$$

Substituting Equation A2 into Equation A1 yields the equation that plays a central role in this paper:

$$s = E * A * T{*}{*}2 \qquad \text{(A3)}$$

where factor E is a so-called force-efficiency factor:

$$E = [\text{Integral}[0,1]dr' \, [\text{Integral}[0,r']dr \; a'(r)] \qquad \text{(A4)}$$

which contains information only on the shape of the acceleration curve during a stroke and which expresses how efficiently force bursts having a specific peak force and total duration are converted into a vertical displacement s.

Overview

Including the production of handwriting subsumed under what Fok and Bellugi in this Section refer to as visual spatial script, the Chinese language provides some unique opportunities to answer questions about the neurological organization of language functions. The papers in this Section demonstrate how such opportunities can be exploited. In contrast with alphabetical and syllabic languages, Chinese may best be characterized as a morphemic language with each written symbol (a character) being nearly always a bound or unbound morpheme and pronounced as a monosyllable. Because the large number of unique configuration of strokes, even though each individual configuration necessarily has to share some common components with other Chinese characters, there are suggestions that visual perceptual processes play a more distinctive role in the perception of Chinese character. Related to this is the possibility that the route from visual script to meaning may be different in some situations for Chinese orthography. Possibly such information processing differences could entail different neurological processes.

The paper by Wang investigated at the phenomenon of mirror writing amongst different groups of Chinese subjects, including pre-school children, school children, normal adults, and patients with cerebral vascular diseases. Since individual Chinese characters are often made up of constituent components (radicals) which are placed in different locations relative to each other within the generally square space occupied by the character, the Chinese language was particularly useful in examining mirror writing. It was found that mirror writing occurred more often when subjects write with their left hand. When learning to write, apart from establishing motor-schemas in the hemisphere contralateral to the hand used, it was hypothesized that corresponding schemas which are mirror images are established in the other hemisphere. This is a very interesting hypothesis and more exploration of its implications is deserved.

The paper by Fok and Bellugi compared the writing errors of ordinary Chinese children and deaf Chinese children who have learned to use the Hong Kong Sign language having its own principles of word formation and syntax, independent of spoken Chinese. The unique characteristics of the Chinese language allowed some interesting comparisons. For example, homonyms in Chinese can have very different visual shapes. The hearing children made a number of errors involving phonetic confusions which tended to be absent in the deaf children, suggesting different mediators for the script. Reflecting the importance of the association between visual form and meaning of written Chinese, furthermore, both types of subjects tended to observe the correct spatial architecture of Chinese characters. The deaf children made sign based errors less frequently found for hearing children. These sign based errors may reflect the formation principles of Hong Kong Sign Language, and the structure of Chinese characters which allowed the opportunity for these errors to occur. This paper showed that recall of written forms of language has a close relationship with the mediators of language.

Tzeng, Hung, Chen, Wu, and Hsi in the last contribution in this volume look at the performance of Chinese brain damaged patients in picture drawing, pseudo-character copying, and writing names for pictures. By comparing the performance of a right-hemisphere damage patient with a left-hemisphere damage patient, the question of right-hemisphere representation of Chinese was examined. There were indications of a separation of the spatial framework and character reconstruction. The right-hemisphere patient showed visual neglect in the left visual field, but not in writing and copying characters. It was concluded that Chinese characters were not processed like pictures. With component strokes of characters being presented stroke by stroke sequentially, requiring mental glueing of the components to arrive at the whole character, a further study looked at the process of visual glueing. Left-hemisphere damage patients had more difficulty in performance of this task. Graphomotor processes played an important role with patients tracing the sequence of strokes with their fingers. The studies with the brain damaged patients provided clear evidences of the predominance of the left hemisphere in processing Chinese words, similar to processing of other languages, dispelling a lot of the myths about Chinese language processing.

Graphonomics: Contemporary Research in Handwriting
H.S.R. Kao, G.P. van Galen, R. Hoosain (eds.)

MIRROR WRITING AND THE DEVELOPMENT OF CHINESE WRITTEN LANGUAGE

Wang Xinde

The mechanism of mirror writing is complicated. There are several hypotheses concerning the mechanism of mirror writing, such as motor hypothesis and cerebral writing center theory. Assessment of mirror writing in preschool children, school children, normal adults and cerebral vascular disease patients with or without aphasia were done in this paper, with the purpose of knowing the relationship between mirror writing and development of Chinese written language, and of understanding the mechanism of occurrence of mirror writing.

MATERIAL AND METHOD OF ASSESSMENT

One hundred and forty-eight subjects were examined and divided into four groups: preschool children, school children, normal adults and cerebral vascular disease patients with or without aphasia.

Preschool Children

This group includes 31 children, 16 boys and 15 girls. The age ranged from 5 to 7 years. Mirror writing and left/right disorientation were examined. Assessment of mirror writing was as follows: ask the children to write down their name, age, numerals "1, 2, 3, 4, 5, 6, 7, 8, 9, 10" and Chinese characters "大，小，田，日，北京， 中華人民共和國 ." (meaning respectively: big, small, field, day, Beijing, and People's Republic of China). Assessment of left/right disorientation: ask the children to do "raise up your left hand" and "touch your left ear with your right hand".

The results of examination showed that 16 out of 31 children have left/right disorientation. Mirror writing occurred in 8 children who were asked to write with the right hand (25.8%) and in 16 with left hand (51.6%). In 16 children with left/right disorientation there were 9 children with mirror writing and 7 children without mirror writing.

School Children

All 40 children of the school group were pupils of the first grade of primary school. There were 23 boys and 17 girls. The age ranged from 6 to 8 years. Mirror writing examination included as follows: ask the children to write down their name, age and numerals "1, 2, 3, 4, 5, 6, 7, 8, 9, 10" and Chinese characters "中華人民共和國, 五星紅旗, 樹, 橋, 船, 尖, 學校, 還, 燈." (meaning respectively: People's Republic of China, Five-starred Flag, tree, bridge, ship, sharp, school, return, and lamp). The left/right disorientation assessment was same as that mentioned for the preschool children group. Partial mirror writing was observed in 4 out of 40 school children when they were asked to write with the left hand, but not encountered in written output by right hand. The data of correlative study of left/right disorientation and mirror writing showed that 2 out of 9 children with left/right disorientation have partial mirror writing and the remaining 7 children have no mirror writing. However, in the other 2 children there was no left/right disorientation, but partial mirror writing was found.

Normal Adults

The normal adults group consisted of 40 right-handed subjects. They were 9 males and 31 females. The age ranged from 22 to 51 years, with an average of 28.1 years. The written language assessment of aphasic examination scale includes spontaneous writing, writing at dictation, copying and filling in blanks. All above mentioned performances were done by left hand. The results revealed that there was no left/right disorientation and only one person (2.5%) with partial mirror writing was observed.

CVD Patients With/Without Aphasia

In this group, there were 27 patients with aphasia and 10 patients without aphasia. Nine out of 27 aphasic patients could write with the right hand and another 18 patients could only write with left hand because of right hemiplegia. In non-aphasic patients, 6 patients had left hemiplegia and the writing was performed with right hand, four patients were requested to write with left hand due to right hemiplegia. Aphasic patients were assessed with the aphasic scale and non-aphasic patients with written language scale. The results showed that in 10 non-aphasic patients, there were six patients without mirror writing using the right hand, and two cases of partial mirror writing were found in left hand writing. In 27 aphasic patients, there was no mirror writing with right hand. There were 6 cases of partial mirror writing and one of total mirror writing when patients were requested to write with left hand in 18 right hemiplegic patients.

The incidence of occurrence of mirror writing and correlation with left/right disorientation were shown in Table 1.

Table 1 Mirror writing, left/right hand writing and correlation with left/right disorientation.

	Preschool N=31	School N=40	Adults N=40	CVD N=37
Mirror writing with left hand	51.6%	10.0%	2.5%	24.3%
Mirror writing with right hand	25.8%	—	—	—
Left/right disorientation	51.6%	22.5%	—	—
Left/right disorientation without mirror writing	43.7%	77.7%	—	—
Left/right disorientation with mirror writing	56.3%	22.3%	—	—

DISCUSSION

In 1985 we reported a case of total mirror writing caused by left thalamic hemorrhage and the mechanism of mirror writing was discussed. The graphic motor-schemas are capable of evoking the appropriate movements from other regions of cortex, and in the case of writing with the left hand it involves a connection between the second left frontal convolution and some area of the right motor cortex by way of the corpus callosum. The fact that learning to write includes an unconscious education in mirror writing, especially with the left hand, implies the establishment, probably in the right cerebral hemisphere, of graphic motor-schemas which are the mirror-image of those which underlie normal writing in the left cerebral hemisphere. In normal right-handed adults the graphic motor-schemas in the left cerebral hemisphere were dominant over the mirror writing motor-schemas in right cerebral hemisphere, with results of appearance of normal writing.

Based on our data, there was only one case of total mirror writing and 37 subjects of partial mirror writing. The partial mirror writing manifested in following forms: (1) Forms frequently occurring in left/right structured Chinese characters, such as "陈," "郭," "[illegible]," which have been written in mirror writing as "[illegible]," "[illegible]," "[illegible]" by reversing of the strokes or left/right miss-placing of the radicals (Figures 1 and 2); (2) Upper-lower structured or left/right asymmetrical Chinese characters. Any mistakes of strokes in left/right direction would cause mirror writing, such as "小," "学," "五", "中," which have been written in mirror writing form as "[illegible]," "[illegible]," "[illegible]," "[illegible]" (Figures 3 to 6); (3) Mirror writing of numerals "S, Ɛ, ߈, Ƨ, ∂, Γ, 01" instead of "2, 3, 4, 5, 6, 7, 10" (Figures 7 and 8). Total mirror writing is illustrated in Figure 9. The results of our examination showed that the incidence of mirror writing decreased with development. The incidence of mirror writing in writing with left hand was higher (51.6%), then it gradually decreased, 10% in school children and 2.5% in normal adults. We also studied the correlation of incidence of mirror writing and left/right disorientation. There was improvement with increasing of age. Percentage of left/right disorientation in preschool children and school children was 51.6% and 22.5% respectively. No left/right disorientation was detected in normal adults. However there was left/right disorientation in preschool children, but mirror writing was found in 56.3% and it was markedly decreased to 22.3% in school children. We considered that left/right disorientation is one of the factors causing mirror writing in Chinese characters, but it could not explain all of the above data.

Figure 1 Handwriting specimen of dictation from a right-handed preschool child who was requested to write with left hand. (Note one Chinese character and two numerals in mirror writing).

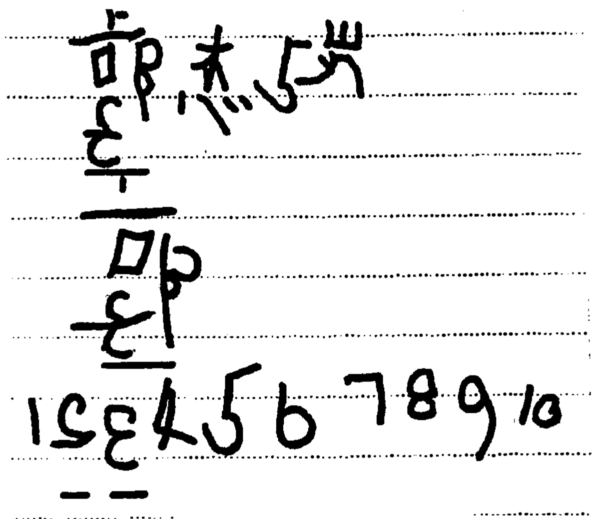


Figure 2 Handwriting specimen of dictation from a right-handed school child who asked to write with left hand. (Note one Chinese character and one numeral in mirror writing).

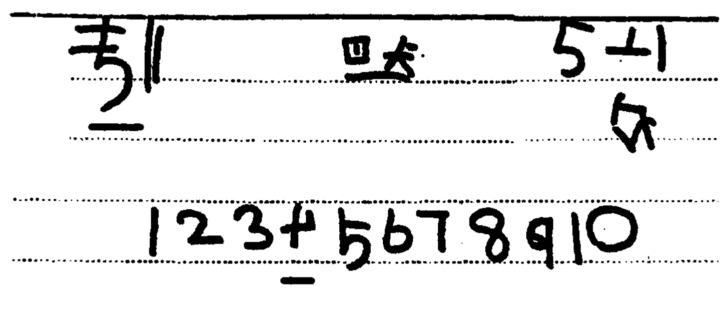


Figure 3 Handwriting specimen of dictation from a right-handed school child who was asked to write with left hand. (Note three Chinese characters in mirror writing).

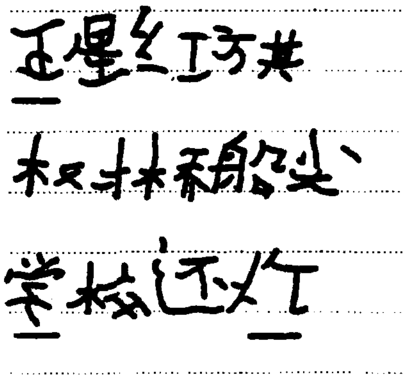


Figure 4 A. Handwriting specimen of dictation from a right-handed normal adult who was requested to write with left hand. (Note three Chinese characters in mirror writing). B. Handwriting of specimen of dictation from a right-handed school child who was asked to write with left hand. (Note one Chinese character).

Figure 5 Handwriting specimen of dictation from a right-handed school child who asked to write with left hand. (Note one Chinese character and one numeral in mirror writing).

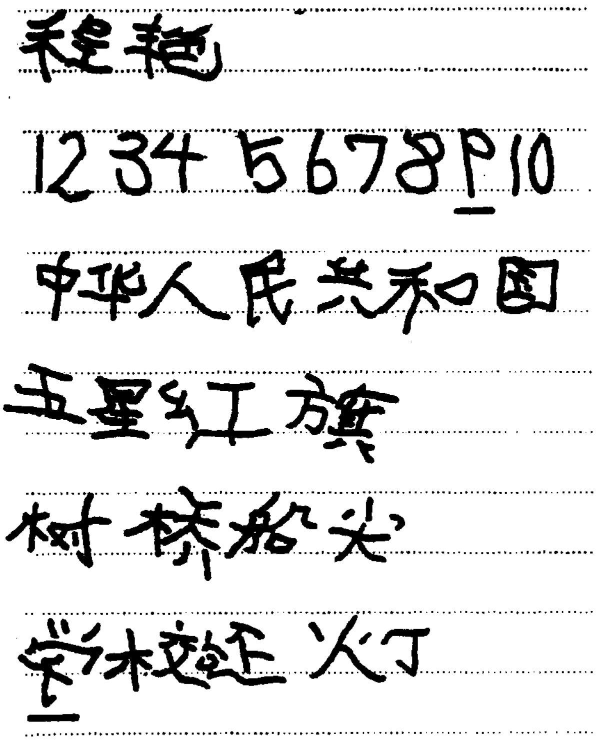


Figure 6 Handwriting specimen of dictation from a right-handed school child who was asked to write with left hand. (Note two Chinese characters in mirror writing).

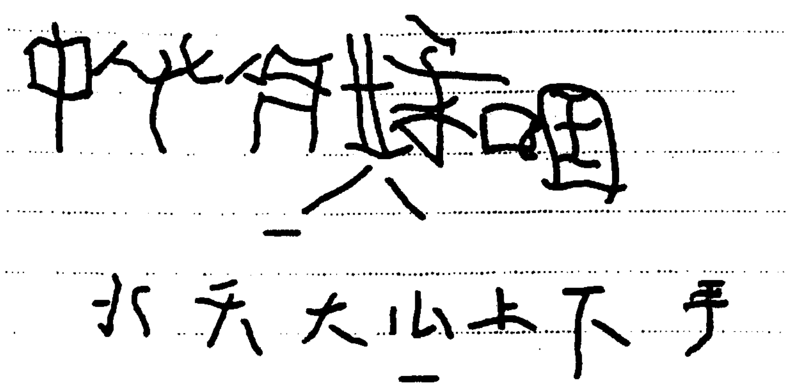


Figure 7 Handwriting specimen of dictation from right-handed preschool child who asked to write with left hand. (Note the Chinese characters and numerals in mirror writing).

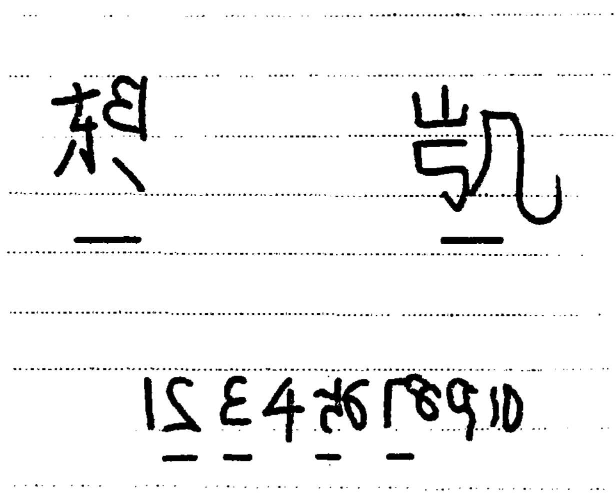


Figure 8 Handwriting specimen of dictation from a right-handed preschool child who asked to write with left hand. (Note four numerals in mirror writing).

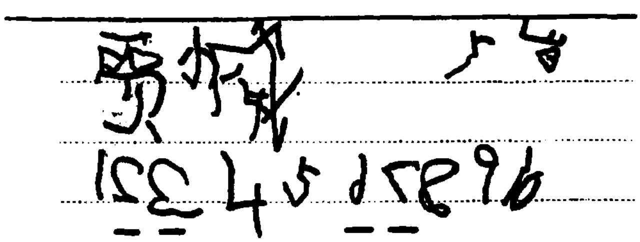
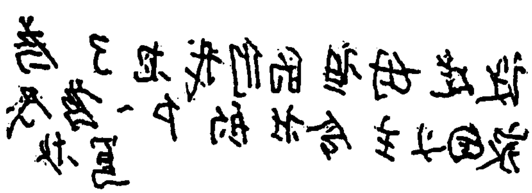


Figure 9 Handwriting specimen of spontaneous writing from a patient with thalamic hemorrhage who was requested to write with left hand. (Note the total mirror writing).



Based on these neuropsychological assessment data, we attempt to interpret the possible mechanism of mirror writing as follows: In normal development of written language, it is possible that graphic motor-schemas in left cerebral hemisphere and mirror writing motor-schemas in right cerebral hemisphere were established. In normal right-handed adults graphic motor-schemas were dominant over the mirror writing motor-schemas, so that in writing with left hand the mirror writing motor-schemas are integrated instantaneously by visual-image of corresponding Chinese characters. In children the graphic motor-schemas and mirror writing motor-schemas in both cerebral hemisphere are not strongly established, particularly, integration of visual-image is weak. In addition to this, there is left/right disorientation in the children, hence, partial mirror writing frequently occurred in children. Mirror writing also was encountered in preschool children when they were asked to write with right hand. It may be possibly related to poor integration of the visual-image.

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THE ACQUISITION OF VISUAL SPATIAL SCRIPT[1]

Angela Fok
Ursula Bellugi

INTRODUCTION

We investigate the beginning stages of writing in deaf and hearing children learning to write Chinese characters. We explore the processing of learning to write in an orthography which is logographic rather than alphabetically based. We examine visual processing for script from the point of view of a special population of Chinese deaf signers who provide a different perspective on understanding the entry into writing.

Alphabetic and Logographic Writing Systems

When linguists study the spoken languages of the world, they are impressed with the way these languages seem cut from a common pattern. It has been claimed that a large part of this common pattern can be explained by reference to the properties of the human organs that produce or perceive sound (Wang, 1973). However, research for over a decade (by now more than 100 papers and several books from the Language Laboratory of The Salk Institute alone), has shown that primary signed languages also exhibit similar kinds of organizational principles, despite their reliance on a different set of human organs for production and perception (the eyes and hands rather than the ears and vocal tract), and, importantly, despite *surface* differences (Klima and Bellugi, 1979).

Spoken languages are *primary* languages, learned by very young children without specific instruction. By contrast, reading and writing are skills that do not come naturally, the way speech does for hearing children and sign language does for children of signing parents. By the time children reach school age, they have effortlessly soaked up the language used around them, be it English, Chinese, or a signed language (Bellugi and Klima, 1982). Learning the written language, however, is frequently an arduous process.

A significant number of children have problems with reading and writing, even with the best of help. This contrast between forms of language — speech versus script — is the more striking, given that written language is invariably based on speech.

All major systems of writing are based on spoken language, though in ways that differ importantly from each other. The alphabetic scripts that prevail in the Western world today are based roughly on sound segments; but the Chinese writing system is different. It is one of the major writing systems now in use in which a significant number of the symbols, called logographs, preserve a direct relation to the morphemes themselves rather than just to their pronunciation. The correspondence between spoken language and written script, then, differs dramatically from alphabetic scripts such as English to logographic scripts such as Chinese. Tzeng and Wang (1983), suggest that the processing strategies developed by skilled readers in order to meet the cognitive demands of the two types of orthographic systems also differ, and they provide evidence to specify the nature of these differences.

The principles underlying Chinese orthography are radically different from those underlying an alphabetic (phonologically-based) orthography such as English. The differences between these two kinds of script are at least three-fold: (1) differences in degree of sound to symbol correspondence; (2) differences in numbers of distinct units; and (3) differences in spatial layout.

In English and other alphabetic orthographies, the unit of *sound to symbol correspondence* is the phonological segment. Letters of the alphabet correspond to phonological segments of the spoken language. Chinese script is made of logographs which do not directly map to individual phonological segments. Rather, the logographs are based on morphemes, and in Chinese one character usually corresponds to one morpheme. Most morphemes can function as independent words in which case the word is represented as a single character. However, many words in Chinese are compounds, and thus are represented by a sequence of two characters.

Since Chinese script is morpheme-based rather than sound-based, it means that some thousands of *distinct units* are necessary to represent all of the words in the language. In contrast, the English alphabet can represent all of its words by means of 26 letters.

The orthographies also differ in the *spatial layout* of the graphemic components representing the word. The letters of an English word are written in linear order from left to right; in some scripts the internal grapheme structure is right to left (e.g., Hebrew); in others it is top to bottom (e.g., Japanese); and in ancient times there was even a method of writing in which the lines were inscribed alternately from right to left and from left to right — the so-called 'boustrophedon.' The graphemic components of the Chinese character are arranged within a square frame. In most characters this frame is itself partitioned in a number of different ways, with components occurring side by side, in horizontal layers, in quadrants, etc. The components are themselves made up of a variety of strokes which derive from a limited set of possibilities, applied in a relatively fixed order. This arrangement of components may be thought of as the *spatial architecture* of the character (Shih, 1984).

Most Chinese characters can be classified into three categories according to the *functional arrangement* of the character, or its parts. Pictograms refer to the characters derived originally from pictures; for example, the character meaning 'sun' derives from a circle that signifies the sun. Ideograms are characters with two or more semantic clues that hint at the meaning of the character; e.g., 'sun' '日' and 'moon' '月' together mean 'bright' '明;' 'people' '亻' and 'words' '言' together mean 'trust' '信.' Phonograms contain a semantic component and some phonetic clue to pronunciation as in the word for 'maple tree' in Chinese is /fun/ '楓.' The corresponding character consists of a semantic component, '木' meaning 'wood'), and a phonetic component /fun/ '風,' which is also the free-standing character '風' meaning 'wind.' The clues to meaning and pronunciation may be quite indirect and are often loosened through historical change. Thus, within the internal structure of the Chinese character there may be only a hint to meaning and only a hint to pronunciation from the phonograms. According to orthographic convention there may be specified places in the spatial layout where the individual components can occur. Many of the semantic components appear to the left or at the top. Many phonetic components appear in the complementary position to the right, or at the bottom. (Further descriptions of the structure and processing of Chinese characters can be found in Hung and Tzeng, 1981; Tzeng, Hung and Wang, 1977.)

Processing of Chinese Script and Sign

There is currently an accumulation of evidence that the processing of this vastly different orthography by hearing speakers of Chinese is quite different from the processing of an alphabetic orthography by hearing speakers of English. Visual procesing seems to be the key for remembering and processing Chinese characters, and in some instances speech recoding accompanying knowledge of the sound to script relationships may even interfere with aspects of processing (Tzeng and Hung, 1981; Tzeng and Hung, 1984). Furthermore, visual processing is the key to remembering signs of Chinese Sign Language, as our previous studies have shown. Deaf Chinese signers code, process, and remember signs based on aspects of their visual form (Fok, Bellugi, Lillo-Martin, in press). For the special population which is the focus of our studies, that is, children who are congenitally and profoundly deaf and are *signers*, there is little possibility of speech recoding. However, since the primary language (i.e., sign language) used by this group of children utilizes the visual spatial mode, we investigate their approach to another set of visual spatial symbols, to learning to write Chinese characters. In sign language, the lexical items are made up of a finite set of hand configurations, spatial locations, and movements, and in a similar manner, the Chinese characters are also made up of a finite set of radicals and forms and these units are also spatially and visually related to one another in writing. Yau suggests some important similarities between the composition of signs and the composition of archaic Chinese ideograms, and argues that the same kinds of constraints have been observed in both types of language (Yau, 1983). Both may be originally motivated (iconic) in form, and both have undergone formal changes that render them more arbitrary.

Our studies of Hong Kong Sign Language show that it is an independent language, not derived from spoken or written Chinese (although there are occasional borrowings from written characters). Hong Kong Sign Language has its own principles of word formation, of morphology, and of syntax. In the experiment which follows, we examine the way in which young deaf and hearing children approach learning to write in a visual spatial script, and examine the relationships between sign, speech, and script.

Differences between Hearing and Deaf Readers of Chinese

There are, of course, differences between the deaf and hearing in their overall level of proficiency in reading and writing, and, particularly, in the ease with which they may acquire written language, given that written languages are invariably derived from spoken languages. However, written languages differ in the extent to which orthographic cues themselves provide a sufficient basis for language processing. In the study presented here, we are interested in examining one consequence of these differences across scripts. We do not, of course, underestimate the problems of deaf children who do not have access to a spoken language learning to read and write in that spoken language; clearly one expects that the lack of access to spoken language will make a difference in reading and entry into writing, in which deaf individuals may to be disadvantaged. In these studies we examine the beginnings of writing for a special group of deaf children — deaf children who are exposed to a sign language — in learning to write in a script that is non-alphabetic.

These exploratory studies may bring out some special visual aspects of the processing of Chinese orthography (as contrasted with processing an alphabetically-based orthography such as English).

PRETEST: WRITING PATTERNS FROM DICTATION

In a pilot study, the first author collected writing errors made by deaf and hearing Chinese children, culled from writing samples to dictation, in workbooks provided by teachers. The preliminary results encouraged us to begin the more systematic studies described in this paper. The samples from deaf children were collected from the Victoria School for the Deaf in Hong Kong, from first and second grade deaf children learning to write Chinese script. The writing samples from young hearing children (aged 6-10) were collected from fluent speakers of Mandarin in America who were first learning to read and write Chinese script, at the San Diego Chinese School by Chi-Lin Shih, research assistant in the laboratory.[2] When the writing errors of the hearing children and the deaf children were analyzed in the same way and compared, we found that the two sets of errors appeared to show interesting differences.

Error Patterns of Hearing Children

We analyzed the errors made by both groups of children, hearing and deaf. We found that typical error patterns across the two groups of children vary significantly. The hearing children often made errors which represented phonetic confusions. One of the typical hearing children's errors includes: a child intended to write the Chinese logograph for ' ' meaning 'already' but wrote instead ' ' meaning 'to use' both of these characters are pronounced /yi/. In this case, the child aimed for one logograph, but produced instead the logograph for a word that sounded exactly the same, but is written completely differently.

Error Patterns of Deaf Children

In contrast, there were *no* sound based errors among the errors made by the deaf Chinese children. The highest percentage of the errors, in fact, tended to observe the correct spatial arrangement of the target, the overall spatial configuration, and sometimes even detailed aspects of components and strokes. The main differences between the target characters and responses tends to lie in the substitution of structurally similar components. For exmaple, a deaf child intended to write the word " 責 " /dzak/ meaning 'responsibility,' but instead wrote the word " 青 " /tsiŋ/ meaning 'green.' The error character has a component in the top spatial position which is correct, and the bottom spatial position has a component which looks highly similar to the target component (both have a rectangular top with two lines across the middle, and they are highly similar visually). In another case, a child intended to write the word " 待 " /doi/ meaning 'to treat' and instead produced the character " 持 " representing the word /tsi/ meaning 'to hold,' with just the substitution of one visually similar component for another. In the errors, the words represented by the characters have no similarity in terms of sound for the deaf children, but do for the hearing children. The deaf children as well as the hearing children tended to observe the correct spatial positions of components of the target item but filled in with other components that are spatially similar; sometimes the error produced an actually occurring different character and sometimes a nonsense character — a nonsense character which was nonetheless spatially and configurationally well formed.

The preliminary results from selected samples of writing errors of two different groups led us to this more systematic investigation of the entry into writing by deaf and hearing children learning to write Chinese script which we spell out below.

THE EXPERIMENTAL STUDY: PICTURE TO CHARACTER CODING

In the pilot study above, the differences we observed between deaf and hearing children were from spontaneous samples to dictation in workbooks; our experiment involves eliciting writing errors more systematically across hearing and deaf children learning to write. We look for differences across the two groups of children that may reveal the nature of their entry into writing Chinese logographs and their hypotheses about the regularities of orthography underlying this script. In order to elicit children's writing, we prepared a booklet of 60 pictures of common objects which are easily represented by frequently occurring characters, described below. We focus here on an examination of the processes of beginning writing in an orthography which itself is mediated in large part by visual-spatial processing.

Subjects

Sixty subjects participated in this test; thirty hearing children from a normal hearing school, and thirty deaf children from two schools for the deaf in Hong Kong.[3] The schools were selected because they used the same textbooks for the teaching of Chinese and followed similar academic curriculae. Grade 1 to grade 3 students were chosen because in these two schools the acquisition of the production of Chinese characters started from grade 1 and at the time when the test was administered the most junior group (grade 1) had had the experience of writing Chinese characters for nine months. The age range of the subjects were from 6-12, shown in Table 1. All deaf subjects were born with profound hearing impairment and were fluent signers of Hong Kong Sign Language. The language program in each of the schools for deaf subjects was aural/oral.

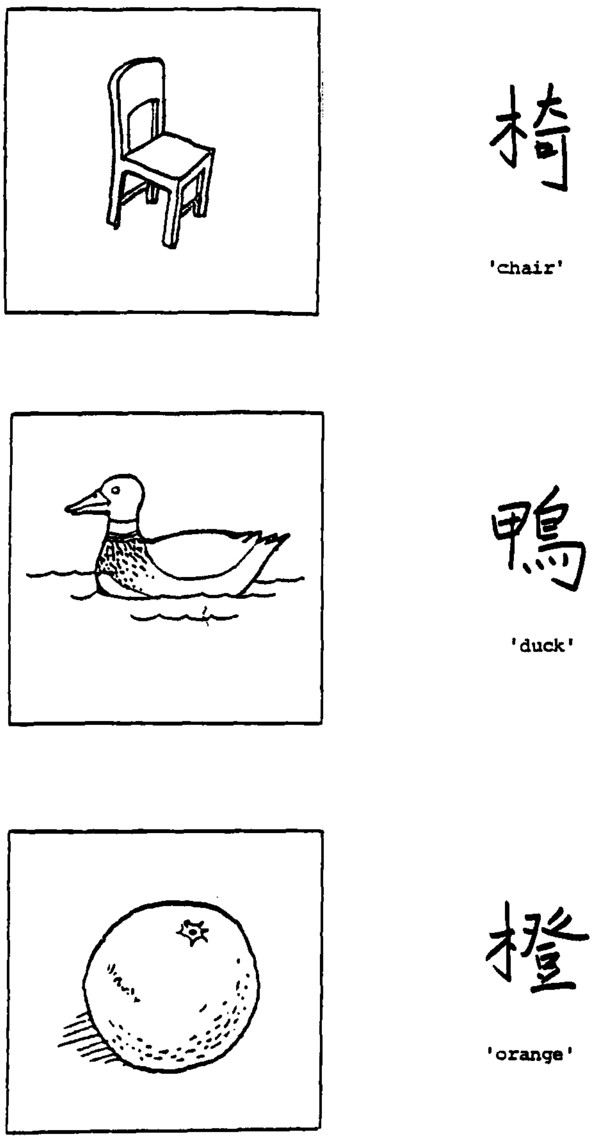
Table 1 Distribution of subjects.

Hearing			Deaf		
Grade	Number	Age	Grade	Number	Age
1	10	6-7	1	10	7-9
2	10	7-8	2	10	7-10
3	10	8-9	3	10	8-12

Procedure

A booklet was prepared, compiled of two sections. The first section consisted of 40 pictures of common objects which are easily recognizable such as a dog, boat, sock, horse, orange, etc. Items were chosen to represent concrete objects and frequently occurring characters, normally learned in the first few grades at school. The second section consisted of ten pairs of pictures, one member of the pair was a picture of an object and the other a picture of the same object involved in an associated activity. Figure 1 shows some sample items from the test. The subjects were asked to write down the Chinese characters appropriate to the pictures, naming the objects or actions. They were told that if they really had difficulty in recalling the characters, they could leave the item blank and come back to it later.

Figure 1 Sample errors and correct responses.



Before the test, the subjects were told that there were no single correct answers, and they should write down what they thought the picture represented. They were also told not to be afraid of making mistakes, for the booklet was meant for all grade levels and it would be given to higher grade students as well, hence some items might be difficult for them. They were encouraged to guess if they were not sure of the answer.

Data Analysis

An analysis of the responses was developed by the first author, categorizing correct and incorrect responses. We will discuss the patterns of responses, examining the major categories of errors. We analyzed separately these responses that were *existing characters* (whether an appropriate response to the picture or not), and those responses that were *non-existing characters* (whether close to characters representing the pictures or not). We also consider some *sign based errors* made by deaf children. Figure 2 shows the classification of Chinese character responses used in this analysis.

Figure 2 Classification of responses (not including omissions).

CORRECT RESPONSE

ERROR RESPONSES

1. ERRORS WITH EXISTING CHARACTERS	2. ERRORS WITH NON-EXISTING CHARACTERS
a. Semantically related to the stimulus picture the stimulus picture	a. Formally related to the characters denoting the stimulus picture
b. Phonologically related to the characters denoting the stimulus picture	b. Not formally related to the characters denoting the stimulus picture
c. No relation to the stimulus picture	

3. SIGN BASED ERRORS

We separated out the responses which were considered *correct responses*, that is, an exact semantic mapping with the stimulus picture. As an example, the children wrote [椅] meaning 'chair' for the picture of a chair. Frequently more than one answer was acceptable; for instance both 'doctor' [醫生] and 'nurse' [護士] were acceptable for the picture depicting a medical person. The errors were analyzed into major groups as follows:

Existing Chinese Characters

Existing character errors that were real characters, e.g., those that would be listed in a Dictionary of Chinese. The existing characters were further subclassified with respect to their relationship to the target. (1) Errors which are *semantically based.* A partial semantic mapping could occur in different ways: either one character of a multi-character Cantonese word was written, for example: the character [電] meaning 'electricity' instead of (電話) meaning 'telephone' or a semantically related term for the object was written: [水果] meaning 'fruit' for the picture of an apple. (2) Errors which are *phonologically* related to the characters denoting the stimulus picture, e.g., [差] for (叉) meaning 'fork.' The target and the response are, in fact, homophones in Cantonese. (3) Characters which had *no relation* to the picture, but were nonetheless existing Chinese characters. For example, one child wrote [小船] meaning 'small boat' for the picture depicting a pie.

Non-existing Chinese Characters

This constituted an interesting and important class of errors which we analyze in depth below. These are characters which are not actual existing characters of Chinese but were in fact '*inventions*' on the part of the children. These inventions could take a variety of forms and might or might not be well formed according to the orthographic regularities underlying Chinese writing. We considered two categories within the non-existing Chinese character responses. (1) Written forms that were *related to the target* characters. These formationally related errors were either identified as preserving the spatial layout of the target characters or containing components which were similar to the target characters. These formationally similar forms generally preserved the spatial architectural form of the target characters, the components and their allowable positions even though they were invented forms; that is they conformed to the orthographic regularities of Chinese characters. (2) Written forms were *not related* to the target characters.

Sign Based Errors

We discuss separately a special class of errors in writing made by the deaf children which appear to be based on principles of Hong Kong Sign Language.

Results

Table 2 shows percentage distribution of the different types of responses collected.

Table 2 Results.

Subjects		Responses		
		Omissions	Existing Characters	Non-Existing Characters
Hearing	G1	39.26%	51.97%	8.6%
	G2	30.85%	59.95%	9.2%
	G3	20.40%	69.65%	9.95%
Deaf	G1	57.11%	34.17%	8.73%
	G2	23.42%	56.10%	20.49%
	G3	25.06%	65.10%	10.23%

Omissions

As Table 2 shows, the number of omissions (or no answers) decreases with each grade attained. This does not necessarily mean that those no response items are all replaced by correct responses. However, it does show that the older the student is, the more confidence they have in producing a written character when given a picture. Table 2 also shows that in the later grades, the deaf and hearing children tended to produce similar percentages of existing characters. Most of the errors across groups are composed of existing characters.

Correct Responses

On the whole, the hearing subjects did better than the deaf subjects, as shown in Table 3. It may be that the hearing subjects had more time for character learning since they did not have to devote a large part of their time in school to auditory training (the language program of the deaf schools was aural-oral based) and character retrieval for them might also be assisted through sound mediation and/or through acts of articulation. Not unexpectedly, there was significant improvement from grade 1 to grade 3 students for both groups.

Table 3 Rate of correct responses.

Subjects		Correct Response
Hearing	G1	37.53%
	G2	51.74%
	G3	63.43%
Deaf	G1	14.96%
	G2	34.88%
	G3	47.15%

Error Analysis

We will now examine the categories of errors made by children. A summary of the nature of the error responses is presented in Table 4, which will form the basis for the analysis given throughout the rest of the paper. First, we examine the error responses that were nonetheless *existing Chinese characters.* We see that the largest proportion were semantically based existing characters in grade 1 for both hearing and deaf, and that the semantically based errors declined across grade levels for both groups. Hearing children showed a proportion of phonologically related errors at all grade levels; but deaf children did not have phonological errors at any grade level. Second we examine error responses that were *non-existing Chinese characters,* e.g., 'invented' characters. Both deaf and hearing children produced formationally related non-existing characters, and deaf children tended to produce more errors that bore no relation to the target than did hearing children at all grade levels. We examine the types of errors below.

Table 4 Classification of errors.

		Error Response				
Subjects		Existing Characters			Non-existing Characters	
		Semantically Related	Phonologically Related	No Relation	Formally Related	Others
Hearing	G1	56.2%	5.6%	4.5%	33.7%	0%
	G2	33.3%	8.7%	5.8%	50.7%	1.5%
	G3	29.2%	7.7%	1.5%	60.0%	1.5%
Deaf	G1	56.3%	0.0%	12.5%	19.6%	12.5%
	G2	31.7%	0.0%	30.9%	37.4%	23.0%
	G3	23.2%	0.08%	39.3%	31.3%	5.4%

Note:
(% of each type of error against total number of errors made)

Errors Which Are Existing Characters

Semantically based errors. Table 4 shows that over half the errors for both the deaf and the hearing children were semantically based existing characters in grade 1, and that the rate of semantically based errors decreased comparably for both the deaf and the hearing children across grades 2 and 3, still remaining high, and similar across hearing and deaf children. Closer inspection of the nature of the errors, however, suggests that there may be a different basis among the hearing children and the deaf children, shown in Table 5. The table classifies semantically based errors into two types: errors that represent a partial semantic mapping between the response word and the stimulus picture (made more frequently by deaf children) and errors that represent writing one character of a multi-character word denoting the stimulus picture (made more frequently by hearing children).

The deaf children's semantically based errors tended to be characters they had written whose meaning shared some semantic category membership with appropriate answers for the picture. The hearing children's semantically based errors frequently involved writing one character representing a multi-character item, instead of the entire lexical label. This suggests a basic difference in the manner of word retrieval, or how a referent is associated with a character form in the two groups of subjects. For the deaf subjects who have no recourse to sound and to the spoken word, but who instead may mediate through sign language, meaning may be one of the main links between picture and character, and hence the children produce errors within the same semantic category as the pictured object. For example, deaf children produced [人] meaning 'man' for the picture of an Indian; while at some level this is not incorrect, it is not a common response for that picture. Deaf children also produced the Chinese character for 'table' [枱] for a picture of a chair (椅); the character for 'chicken' [雞] for a picture of a duck (鴨). The character for 'foot' [腳] for the picture of socks (襪); the character for 'to sing' [唱歌] for the picture of a piano (琴). The hearing children instead tended to produce errors mediated through the relationship between the spoken word and the character. Often the error consists of one character of a disyllabic Cantonese word that is, the response is one part of a multi-character word. Hence the semantically based error of the hearing children were mostly morpheme syllable omissions. Consider the picture of an Indian, which in Chinese is commonly labelled as the compound of the word 'red' [紅] and the word 'foreign' [番], a multicharacter word in Cantonese. A deaf child wrote [man] as reported above; and a hearing child wrote only [red], which is the first part of the lexical item. The drawings are all rendered in black and white, so the hearing child is clearly not labelling the color of the drawing; hence we assume that the hearing child's error comes from writing down one syllable of a two syllable word, showing mediation through spoken Cantonese. Other errors of a similar nature made by hearing subjects include: [耳] meaning 'ear' for the picture of earrings (耳環); [香] meaning good smell for the picture of a banana (香蕉), etc. Thus, the hearing child's responses appear to show mediation through spoken language.

However, there is no indication that the deaf child goes through spoken form of Cantonese but may be either influenced by the language he uses or by referencial meaning of the picture in coming up with a response character.

Table 5 Semantically related errors.

Subjects		Errors: Partial Semantic Mapping	Errors: Syllable/Morpheme Omissions
Hearing	G1	2	48
	G2	6	17
	G3	6	14
Deaf	G1	55	8
	G2	40	4
	G3	23	3

Note:

Partial Semantic Mapping = Partial semantic mapping between the response word and the stimulus picture.

Syllable/Morpheme Omission = The response contains only one character which forms a part of the multi-character word denoting the stimulus picture.

Table 6 Phonologically related errors.

		Error Response			
Subjects		Type 1	Type 2	Type 3	Type 4
Hearing	01	0	0	0	5
	02	0	0	2	4
	03	0	0	1	4
Deaf	01	0	0	0	0
	02	0	0	0	0
	03	0	1	0	0

Note:

Type 1 Errors = Response word similar to target word in initial consonant.

Type 2 Errors = Response word similar to target word in syllable final.

Type 3 Errors = Response word similar to target word in tone.

Type 4 Errors = Response word is a homophone to target word.

Phonologically related errors. If we examine the phonologically related errors (Table 6) we find a total of 16 errors made by the hearing children and only one error made among all the deaf subjects. As can be seen from Table 6, most of the errors made by the hearing subjects were homophonous to the target characters. For example the character [頸] /geŋ / meaning 'neck' was written instead of the target word (鏡) /geŋ/ meaning 'glass,' and the character [時] /si/ meaning 'time' was written instead of the target word (匙) /si/ meaning 'key.' Note that the written character forms are totally unrelated to the target forms. As for the one error made by the deaf subject, he wrote [境] /giŋ/ meaning 'condition' for (鏡) /geŋ/ meaning 'glasses.' This error is not just phonologically related to the target character, it is also *formationally* similar to the target as well, the two right-sided components being formationally identical. Hence we seen, in this group of errors, spoken Cantonese plays an important part in character retrieval for the hearing subjects but essentially not at all for the deaf subjects. Figure 3 presents some of these phonological errors.

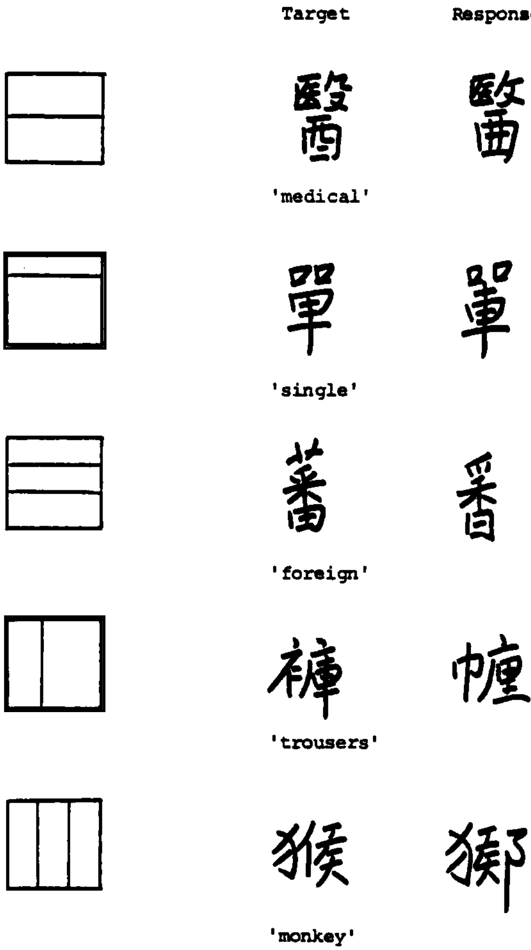
Figure 3 Errors that are similar in sound to the target characters.

Errors Which Are Non-Existing Characters

Until now we have been discussing error patterns in which the deaf and hearing children wrote an existing character, albeit not an instance of an acceptable form for the stimulus picture. Even more interesting and important for revealing hypothesis about orthographic regularities are those errors which result in *non-existing* characters. This is an important class of errors for understanding the child's approach to writing Chinese characters, since the child has not just memorized the characters presented to him, he is providing evidence of his 'inventions' of character forms. We analyze some of these inventions below.

Formationally related errors. A large proportion (over 90%) of the invented characters of hearing and deaf children in this category were well formed characters, i.e., conforming to the structural rules of existing Chinese characters, demonstrating that both groups of subjects had extracted regularities about the formal properties of Chinese characters. For example the error word [[illegible]] was written instead of the character (醫) meaning 'medical.' Both the error and the target having the same architectural form " [illegible] ." The top pieces on the left of the two words are identical whereas the top pieces on the right are different but resemble one another closely in shape. The bottom piece of the error [[illegible]] however is a non-existent form which again resembles the target shape " 酉 " very closely. If we take another error [[illegible]] deaf schools was aural-oral based) and character retrieval for them might also be assisted through sound mediation and/or is a non-existent form which again resembles the target shape " [illegible] " very closely. If we take another error is a minimal free form and can occur independently in other characters as radicals. The top form [爫] occurs in " 暖 " (meaning 'warm') and " 浮 " (meaning 'to float'), the middle part [禾] can occur alone, or form a side radical as in " 科 " (meaning 'subject') or base radical as in " 秦 " (a common family name) and the bottom part [日] can exist alone, or form top and bottom parts of a character as in " 旱 " (meaning 'dry') and " 昔 " (meaning 'past'). Figure 4 shows sample formationally related target and error pairs made by deaf children which are non-existent character forms.

Figure 4 Deaf children's responses that ate formationally similar to the target characters in spatial architecture, components and arrangements.



In Table 7, all errors consisting of invented characters were grouped according to the architectural forms of their target characters. The table is divided into nine groups of error types, eight of those representing the different basic architectural structure of Chinese characters, and the last type including all errors which had no relationship with the target word at all. Results tabulated again shows that a large proportion (80%) of the inventions made were formally related to words representing the target pictures. Note that the deaf and hearing children alike showed sensitivity to visual-spatial aspects of character formation: the architecture, the components, their arrangements and their spatial layout, and even configurational aspects in which the subcomponents tended to be orthographically legal and in allowable spatial positions.

Table 7 Formally related errors.

		Error Response								
Subjects		Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9
Hearing	G1	1	19	2	2	0	0	0	0	0
	G2	2	21	3	9	1	0	0	0	1
	G3	6	20	5	7	0	1	0	0	1
Deaf	G1	4	17	0	0	0	1	0	0	13
	G2	6	24	5	7	4	6	0	0	32
	G3	3	25	3	2	1	1	0	0	6

Type 1 = Whole word unit, the strokes combined to form one unit e.g. '車' (car).

Type 2 = Horizontal left-right construction e.g. "椅" (chair) which is a combination of "木" and "奇".

Type 3 = Horizontal left-mid-right construction e.g. '猴' (monkey) which is a combination of "犭", "亻" and "矦".

Type 4 = Vertical top-bottom construction e.g. "琴"(piano) which is a combination of "珏" and "今".

Type 5 = Vertical top-central-bottom construction e.g. "蕃", the first character of the word 'tomato' and it is a combination of '艹', "釆" and "田".

Type 6 = Vertical plus horizontal construction e.g. "護", the first character of the word 'nurse' and it is a combination of "艹", "言", and "隻".

Type 7 = Total inclusion construction e.g. "國" (country) which is a combination of "囗" and "或".

Type 8 = Partial inclusion construction e.g. '向' (to face) which is a combination of '冂' and '口'.

Type 9 = Characters which are not related formally to any of the target characters denoting the stimulus picture.

Other errors. Even the 20% belonging to the unrelated category (type 9 errors in Table 7), while they were non-existing characters and not semantically, phonologically, or formationally related to the target, were yet well formed in both hearing and deaf subjects. For example, one of the errors from a deaf subject was [[illegible] 子] for the target picture of a piano which should be written as (琴). The first character of this error response [[illegible]] is clearly a nonsense word and has no relationship in form whatsoever with (琴) the target. However, if we examine the composition of the character, it resembles closely an existing character " 橋 " meaning 'bridge.' Both the invented character and the character for bridge are left-right construction words; the left piece of both characters look similar, with the former piece having an additional stroke [丿] at the top. The right piece structures are both two-tier constructions with [口] forms on each tier. The main difference between these two-tier constructions on the right rests on the top piece of the structure: the invented character has [冂] while the actual character has " 夭 " in its place. However since the word whose form " 橋 " is not the target word of this error [[illegible]], it is not certain what target the subject has in mind, because there is no trace in the resulting character which bears resemblance to the words (in this case (琴)) related to the stimulus picture.

Most of the errors classified in the unrelated category (type 9 in Table 7) were collected from deaf children. This suggests that the deaf children, having no phonological clues to words to hold onto, relied primarily on their knowledge of orthographic rules extracted from their knowledge of characters to create their responses, and this resulted in more formal errors which are off the mark of acceptable targets. However, during the process of exploration with forms, deaf subjects produced very few impossible character forms. Most of their nonsense constructions were completely within the bounds of the implicit rules governing the structure of Chinese characters.

Thus the deaf children, as well as the hearing children, are following the orthographic regularities of Chinese characters in creating these non-existing forms. The response may have no semantic, formational, or phonological relationship with the target, but even though it is invented 'nonsense,' it is nonetheless structurally well formed, rule governed. Among this special class of errors made only by deaf children, there were a number of errors that appear to involve creating characters by borrowing principles from Hong Kong Sign Language.

Sign Based Errors

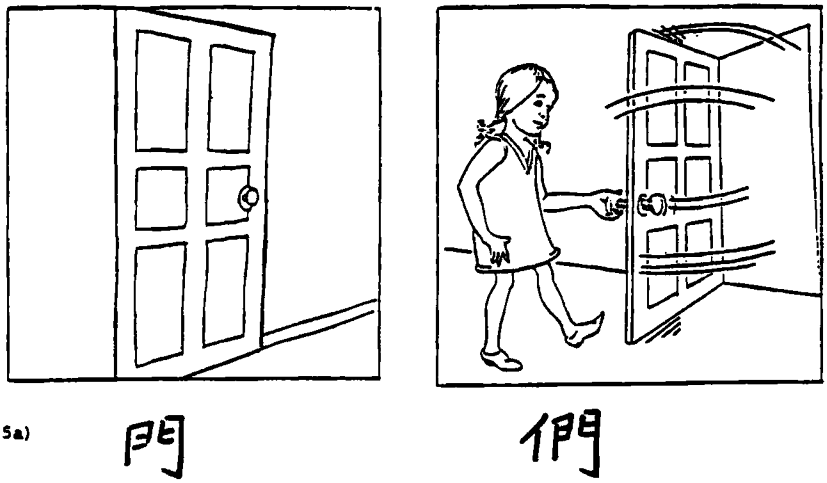
While engaging in the process of manipulating the different character parts in order to produce a written form, the deaf subjects sometimes appeared to call upon their knowledge of the formal principles governing the formation of lexical items and morphological processes in Hong Kong Sign Language. We have begun formal studies of Hong Kong Sign Language, finding that there are classes of signs and of grammatical operations on signs that are indigenous to the sign language, not borrowed from the surrounding spoken or written languages. Hong Kong Sign Language has its own principles for forming lexical items, for compounding (not derived from compounding in Chinese), for classifiers (not related to classifiers in Chinese), for special classes of signs called size and shape specifiers, and for the formal relationships between classes of nouns and their related activity verbs. These principles involve manipulation of sign forms in space, distinctive use of the two hands in forming multimorphemic signs, and superimpositions of distinct movement features to mark derivational and inflectional processes. Some of the non-existing character errors which deaf children created appeared to be based on such sign language word formation principles.

On the second part of the test, we showed pairs of pictures, one of which represented a concrete object and the other represented an action in relation to that object. Both hearing and deaf children tended to give a single word response to the object and to describe the action with a phrase. One pair of pictures (Figure 5a) depicts a door and a girl opening a door. A deaf subject wrote the character correctly [門] for the picture of a door. But for the picture showing a girl opening a door, the subject wrote down a single form [們] which is an existing character, a plural suffix in Chinese. It might seem very puzzling at first that the deaf child would label the act of opening a door with a plural marker in Cantonese. A plausible 'explanation' might come from an examination of principles of sign language. If we examine the basic lexical composition of Hong Kong Sign Language, we find that root morphemes can be combined both simultaneously and sequentially to form more complex single units. For example, the classifier sign representing a person is formed with a closed handshape with the thumb and little finger extended (as in Figure 6a) and the sign representing two persons together is formed by adding a similar hand shape with the other hand. The two hands together could then be treated as one form and can undergo operations as a word unit as in signing PERSON-GO, PERSON-SIT, PERSON-FALL or TWO-PERSONS-EXCHANGE. The same handshape is combined simultaneously with other parameters to form morphologically complex signs. In labelling the picture of a girl opening a door, the deaf subject put the radical [person] [亻] next to the character for door [門] and turned it into a basic unit, similar to the kind of compilation he might have made in his sign language. In so doing, he came up with a resulting form [們], perhaps intending it to mean a person next to a door, but unintentionally producing an actual character in Chinese designating plurality. If our interpretation is correct, this example is a case arguing that character selection for deaf children may be mediated by the structure of their sign language.

Another example that may be construed as an intrusion of principles from Hong Kong Sign Language is illustrated in Figure 5b. In this example, the deaf subject put down the character [飛] (meaning 'to fly') for the picture of a rocket, using it as a nominal. For the second picture, which shows a rocket taking off, the deaf subject repeated the character, but added

Figure 5 Character errors based on sign language principles.

5a)



5b)

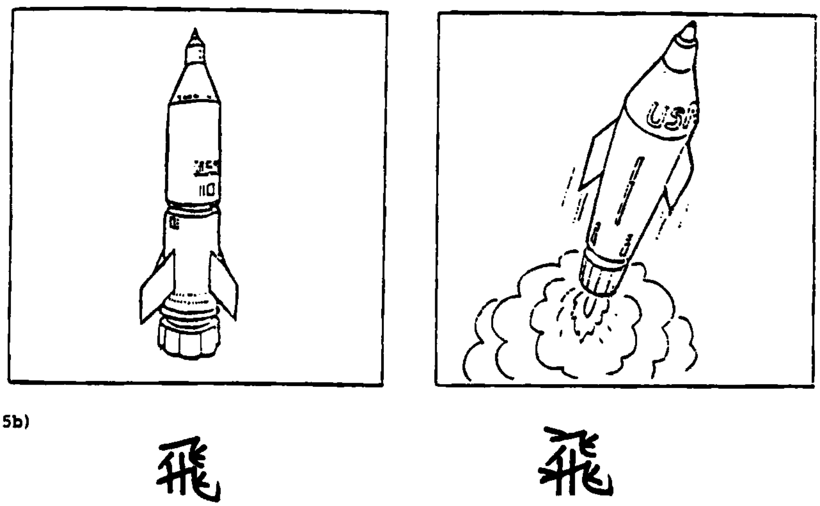
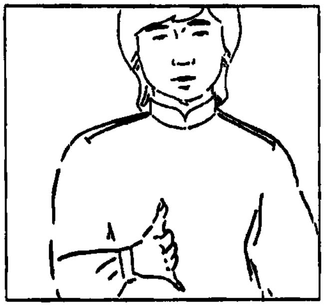
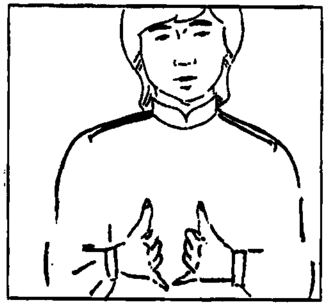


Figure 6 Examples from Hong Kong sign language morphology.

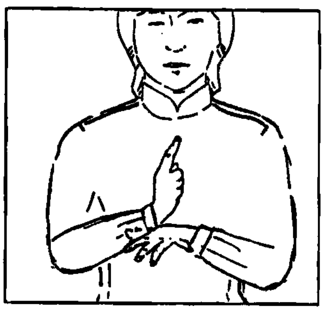


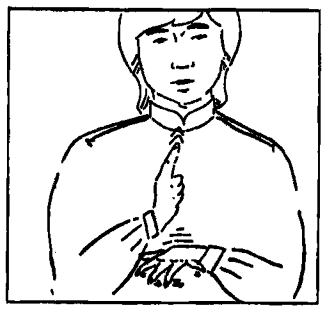


6a)

ONE PERSON

TWO PERSONS





6b)

ROCKET

ROCKET MOVING UP

two additional lines to the character [飛], perhaps to denote movement or action!

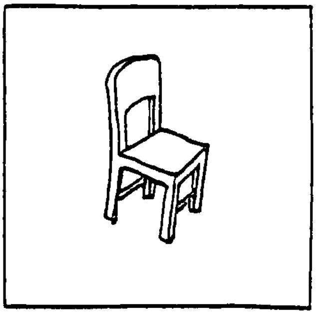
This is a practice which clearly violates the rules of character formation in Chinese, but interestingly, it conforms very well to principles of sign formation which distinguish formally related nouns and verbs. In Hong Kong Sign Language, the basic form for 'rocket' is represented by the hand shape shown in Figure 6b in contact with a base hand; to denote action, as the equivalent of 'rocket taking off,' one hand move upwards with the fingers on that hand continuously flicking. In the child's rendition of the character, this movement is formalized by adding two slanting lines to the basic form (飛), presumably to denote upward motion. Again the child may be using a principle from the distinction between nouns and their formally related verbs in Hong Kong Sign Language to form a character, this time resulting in non-existing character that is not a possible form.

Such borrowing of principles from sign language did not only occur at the lexical and morphological levels, it was also found on occasions when the names of objects were invented by the child. For example, a deaf child apparently did not know how to write the character for 'chair' (椅) so he substituted by writing three characters: [四 方 汧] meaning 'four, square, shape.' This strategy of naming objects by specifying aspects of their size and shape is very common in sign languages, as one of several compounding processes. Moreover, we also note from the above example, the word [汧] meaning 'shape' had its two-side structures written in the reversed order. The actual word has three slanting lines on the right, like this "形 ." In displacing the right side-structure to the left, the subject changed its shape and made it conform with other three-stroke side-structures in Chinese, as in words like " 池 " (meaning 'pool'), " 游 " (meaning 'to swim'). Other examples from deaf subjects using size and shape specifiers include [圓 汧] meaning 'round, shape' for (pie) and [四 長 汧] meaning 'four, long, shape' for (gum). Such sign based character forms are illustrated in Figure 7. In Hong Kong Sign Language, this principle of naming objects with size and shape specifiers is very common.

Besides inventing names by using size and shape specifiers, the deaf subjects also invented names by picking out certain characteristic features or functions of the objects pictured. Hence a picture of a violin was written in characters as [發 聽] meaning 'give out, listen;' piano was written as [發 聽 唱] meaning 'give out, listen, song;' earring as [耳 石 黃] meaning 'ear, stone, yellow.' This strategy of naming objects by picking out their representative features or functions is one of the basic methods of word formation in sign language and in this test, the deaf subjects appear to have applied it to writing Chinese characters as well.

The deaf child perceives rules in his sign language, and uses them in constructing new signs (Bellugi and Newkirk, 1981; Padden and LeMaster,

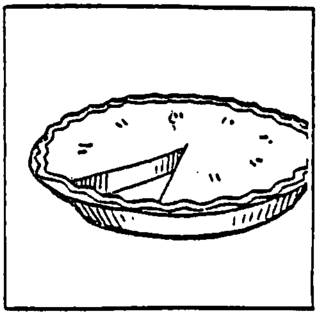
Figure 7 Sign based errors — size and shape specifiers.



'chair'

四 方 形

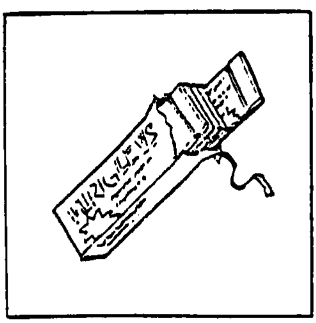
'four square shape'



'pie'

圓 形

'round shape'



'gum'

四 長 形

'four long shape'

1985; Newport and Meier, in press). When faced with constructing Chinese characters in these early stages of learning to write, he then appears to apply the same kinds of rules borrowed from sign language to the formation of characters. What is important here is the active construction of characters on a rule governed basis. Both deaf and hearing children show appreciation of orthographic regularities in Chinese character formation; in addition, deaf children show evidence of mediation from sign language, and of rule generation based on sign language principles.

DISCUSSION

From the results, we can extract the similarities and differences between young hearing and deaf children in their early approaches to literacy and writing. We focus primarily on the nature of the errors made by both groups of children in their beginning approach to writing Chinese characters. we find that some aspects of learning to write are clarified dramatically by considering the acquisition of writing in Chinese, rather than an alphabetically based orthography such as English (see, for example, Hanson, Shankweiler and Fischer, 1983). In the process of learning to write characters, we find first of all that the hearing children bring their knowledge of the sound structure of spoken Cantonese into play in that some of their errors have a phonological source, i.e., based on homophones in spoken Cantonese. These phonologically based errors often had different numbers of components, different strokes, different spatial layout. Thus the target character and the error had nothing in common in terms of shape or spatial configuration. Furthermore, the hearing children also demonstrated their dependence on the sound label representing the objects by putting down one character of a multi-syllable/morpheme word, thus showing mediation through the relationship between the spoken word and the characters. Second, without the input of spoken Cantonese, the deaf children made essentially no errors based on phonological dimensions and very few based on any aspect of mediation through spoken words. However, the deaf children did make use of greater exploration of forms, as well as far more semantically based errors, in which the character written bore a semantic relationship with the target.

But perhaps the most revealing types of errors made by the children were those involving an invented character form; e.g., non-existing Chinese charaters. The children played with forms and made use of the spatial organization of characters to invent written configurations that were non-existent characters in Chinese. When children learn characters in the school system, they are presented with written forms as integral units; each character is visually-spatially distinct. From these distinct units, teachers may point out the semantic or phonetic signifiers. However they are unlikely to analyse the complexity and regularities underlying the architectural forms of the characters which the children are asked to memorize and reproduce in the early grades. From our results we see that deaf and hearing children alike, in the first years of learning to write, actively discover the internal regularities and that they make use of such regularities in creating new character forms. Often target and error pairs made by deaf and hearing children alike were strikingly similar in spatial architecture and spatial organization. Furthermore these internal spatial configurations are always have allowable parts in their allowable locations within the framework of a character. Importantly, even in the case when the invented characters are unrelated to the target, they are almost always perfectly acceptable character forms following all the implicit rules of character formation.

Finally, we find that deaf children bring their own knowledge of sign language to the process of constructing characters. The evidence suggests that the actively seek to impose principles of sign construction borrowed from Hong Kong Sign Language and apply them to the written form of Chinese they are learning. This is possible because sign and script are both languages which utilize space in the creation of their formal units. From our experiment, we see that the children extract the rules of one visual spatial language, that of sign language, and apply them to another form of visual spatial language, that of written Chinese script.

FOOTNOTES

1. This work was supported in part by National Institutes of Health Grants NS 15175, NS 19096, HD 13249 and by National Science Foundation Grant BNS83-09860 to Drs. Ursula Bellugi and Howard Poizner at the Sålk Institute for Biological Studies. we are very grateful to Edward S. Klima, Ovid Tzeng, and Daisy Hung for their contributions to this paper.
2. A working paper contrasts the errors in this pretest made by deaf and hearing children, in terms of spatial architecture, spatial configuration, phonetic and semantic errors, (Shih, Fok, and Bellugi, 1985).
3. The studies were conducted at the Hong Kong School for the Deaf; the Canossa School for the Deaf; and St. Stephen's Primary Girls' School. We are very grateful to the principals, the teachers, and to the young deaf and hearing children for their participation in these studies that examine the beginnings of writing in Chinese.
4. Subject responses are in square brackets [ ] and words denoting the stimulus pictures in round brackets ( ); meaning is in single quotation marks, and phonetic symbols are in slashes / /. Sign glosses are presented in capital letters.

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PROCESSING CHINESE LOGOGRAPHS BY CHINESE BRAIN DAMAGED PATIENTS

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Daisy L. Hung
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Mao-Song Hsi

INTRODUCTION

Reading research has regained the attention of experimental psychologists in the last two decades (Tzeng, 1981). The problem has been attacked from different perspectives with various experimental paradigms. First, there are studies which record patterns of eye movement and relate them to various phases of information pick up during reading comprehension (Carpenter & Just, 1977). Second, there are studies which look into specific characteristics of word perception, e.g., the word-superiority effect, and attempt to build interactive models of human information processing (Rumelhart, 1985). Third, there are studies which examine the consequences of becoming literate in more than one writing system. For example, differences as subtle as phonemic awareness and as general as problem-solving strategies have been observed in such comparative reading studies (Scribner & Cole, 1978; Liberman, Liberman, Mattingly, & Shankweiler, 1980; Tzeng & Hung, 1981).

Fourth, an emerging set of studies have focused on patterns of deficits manifested in the reading performance of various types of aphasic patients. This line of research cut across the previous three, which consisted of models and theories derived from testing normal subjects, by testing the performance of patients known to have different types of neurological damage on one hand, and linguistic behavioral disorders on the other hand. The merge proves to be very fruitful on both empirical as well as theoretical grounds. Since the publication of Marshall and Newcombe's seminal work (1973), hundreds of journal articles and book chapters have been devoted to further specification of the unique characteristics of various types of "acquired dyslexia" (Coltheart, Patterson, & Marshall, 1980) and how they may relate to different types of aphasic syndromes. An important, and no less interesting, observation is that patterns of reading disorders depend not only on the location of brain damage but also on the typology of the writing system. Such observations have led many investigators to conclude that lexical access of words written in different scripts (e.g., alphabetic vs. logographic) is accomplished by different neurolinguistic pathways which probably are represented by different special functions of the two cerebral hemispheres. Thus, Henderson (1982), after an extensive and critical review of the literature, offers a tangible dichotomy based on the specialization of the two cerebral hemispheres. An example follows in Table 1.

Table 1 Henderson's (1982, p. 208) tangible dichotomy based on the specialization of the two cerebral hemispheres.

	LH	RH
Specialized for	All English words English Pseudo Words	Concrete English words Words
	Kana *Pinying*[a]	Arabic Numerals *Hanji (Kanji)*[a]
Selective Impairment	Deep Dyslexia	?
Processing Mode	GPC	Direct Access (non-GPC)

Note:
[a] This line was added by the present authors based on the scheme proposed by Henderson.
GPC=Grapheme-Phoneme-Conversion

In this paper, we will present two sets of studies. The first study looks into the issue of the right-hemispheric representation of Chinese logographs by examining the writing errors of patients with right or left hemisphere damage. We will show from the data we have obtained that there is no evidence to support the hypothesis of right hemispheric representation of Chinese characters. Given this position, we will then present our next set of studies which attempt to examine the role of graphomotoric codes in the processing of Chinese logographs.

CHINESE CHARACTERS ARE NOT REPRESENTED AS PICTURES

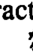
Throughout the history of hemispheric specialization research, there has often been speculation about the possibility that the functional organization of a literate brain may be related to the type of written script one has acquired in learning to read. From Dejerine (1891) to Hinschelwood (1917) in the 19th century and from Luria (1970), Hecaen and Kremin (1976), Benson and Geschwind (1969), and Zaidel and Peters (1981) in this century, evidence has been provided to show selective sparing of reading one type of script despite severe impairments in the reading of other scripts in bilingual aphasic patients. Recent findings of selective impairments in the reading of Kanji and Kana script by Japanese aphasic patients within a single spoken language have strengthened the hypothesis of the scriptal effect on cerebral organization (Sasanuma, 1980; Hung & Tzeng, 1981). As we can see from Table 1, Henderson (1982), though not without doubt, has nevertheless assigned the reading of Hanji (or Kanji) to the right hemisphere.

Basically, there are two reasons why Chinese characters are thought to be processed by the right hemisphere. The first one points to their lack of grapheme-phoneme correspondence and thus their recognition does not require the use of the so called grapheme-phoneme-conversion (GPC) rules which presumably are employed by the left hemisphere to decipher the printed symbols (Coltheart, 1980). The second refers to their unique spatial layout and thus their recognition should be handled better by the right hemisphere which presumably specializes in visual-spatial processing (Gazzaniga & Sperry, 1967). While on the surface both reasons seem to make sense in view of current literature on hemispheric specializations, their validity has never been empirically demonstrated. In fact, closer examination of the existing literature suggests that both reasons are wrong.

With respect to the question of phonological recoding in the visual processing of Chinese characters, a number of studies have established beyond doubt the necessity of speech recoding in reading words or sentences written with Chinese logographs by Chinese readers (see Hung & Tzeng, 1981, for a critical review). The remaining question is how can this phonological recoding process be accomplished if the logographs do not have the clear grapheme-phoneme correspondence. Again, a closer look suggests that even though the script/speech relation is opaque in Chinese logographs, a majority of characters are in fact phonograms, i.e., many characters share a common phonetic component to give a hint about their pronunciation (Wang, 1973, 1981). Thus, with the knowledge of how to pronounce a limited number of basic characters, and of orthographical rules in the construction of characters, readers of Chinese can in fact make reasonably successful guesses about how to pronounce characters that share the same phonetic component, even those characters that they have never encountered before (Zhou, 1976). The procedure involved in this type of grapheme-sound-conversion is of course very different from that involved in the GPC rules advocated by Coltheart (1980). But it is similar to Glushko's (1979) activation-synthesis model of word naming. Indeed such a procedure of naming by analogy was proposed by Tzeng (1981) as one of the two mechanisms in speech recoding and was recently thought to be used by fluent readers of English for most words (Kay & Marcel, 1981; Seidenberg, 1985). Empirical evidence for the operation of this type of speech recoding in reading Chinese has been provided by Lien (1985) in her master thesis. Therefore, there is no compelling reason to believe that Chinese characters must be processed in the right hemisphere simply because they cannot be operated by GPC rules.

The other reason for associating the processing of Chinese characters with right hemispheric functions is even more absurd than the first one. Because of their unique spatial layout, Chinese characters have been regarded as something like pictures and hence it has been stipulated that they are processed in the right hemisphere. Visual hemi-field experiments with a tachistoscopic recognition paradigm have indeed *occasionally* produced a left visual field advantage, implying a right hemisphere dominance for the processing of Chinese characters (Hatta, 1977; Sasanuma, Itoh, Mori, & Kabayashi, 1977; Tzeng, Hung, Cotton, & Wang, 1979). However, a critical review of relevant literature suggests that the observed left visual field advantage may be due entirely to perceptual factors and may have nothing to do with linguistic processing (Hasuike, Tzeng, & Hung, in press). Using an entirely different experimental procedure, So, Potter, and Friedman (1976) also demonstrated that Chinese characters are processed in a manner very different from picture processing.

Since most studies so far examine only the perception and/or recognition aspect of character processing, it is important to look at this issue by examining the writing errors committed by patients suffering from either right or left hemisphere damage. In May 1985 we were able to identify two patients, one with right hemisphere (RH) damage and the other with left hemisphere (LH) damage, from the National Taiwan University Medical Center. The case histories of these two patients are presented in Table 2.

Two types of tasks were administered to these two patients. The first type consisted of copying tasks which included copying 10 geometric graphs and 25 pseudo-characters (i.e., orthographically permissible non-characters such as  and ) and 25 non-characters (e.g.,  and ) which were presented one by one in random sequence to the patient. The latter was asked to copy each presented non-character onto a pre-arranged 7x10 matrix, starting from the upper-left corner. The patient was told to fill up the cells in the matrix with the presented characters. The second type was semi-spontaneous in nature and included drawing 10 different pictures upon hearing the names of the objects, writing down 40 multiple-character words according to the names of pictures compiled into a booklet, and constructing 10 sentences as instructed by the tester.

Performance of patients with regard to these two types of tasks shows several intriguing and interesting contrasts.

1. With regard to the copying of geometric figures, the LH damaged patient showed perfect performance, whereas the RH Patient showed typical visual field neglect (Warrington, James, & Kinsbourne, 1966). Samples of their copies are presented in Figure 1.

Table 2 Case histories of the right and left hemisphere damaged patients.

	LH Patient	RH Patient
Age	55	55
Handedness	Right	Right
Years of Education	16	9
Occupation	Mechanical Engineer	Driver
Native Language	Taiwanese Mandarin	Cantonese Mandarin
Onset time	1-8-84	12-23-84
Hemiplegia	No defect	Defect
Hemianopsia	No defect	No defect
One side neglect	No defect	Defect
Speech diagnosis	Conduction aphasia Agraphia alexia	Normal
Localization	Parietal lobe	Basal ggl.
CT scan	Cerebral infarction in the left posterior parietal area in the territory of the left MCA causing definite mass effect or midline displacement.	Midline shifted to the left side with compression of right lateral ventricle, an area of increased attenuation at right basal ggl. and also right deep parietal lobe. Postoperative change is noted at right temporal lobe.

2. With regard to the copying of real characters when they were presented in isolation, both *right* and *left* hemisphere damaged patients made no mistakes.
3. With regard to the copying of pseudo-characters and non-characters onto the 7×10 matrix, the patterns of results from these two types of patients were of utmost interest. The LH damaged patient was able to copy most of them with occasional slippages (i.e., hesitation, erasing initial copying and making revisions, and deletions) on some non-characters, as if the patient was trying to apply orthographic rules without success. In addition, the patient was filling up the matrix with the copied characters from the designated position in an orderly fashion. On the other hand, the RH patient started to copy the first presented

characters onto the designated position, followed by a strong tendency to copy subsequent characters onto the right side of the matrix, *neglecting* the left hand side of the matrix. Nevertheless, for those pseudo-characters that were copied down, no signs of hesitation nor any mistake were observed. In other words, visual neglect was observed for the spatial framework, but not for characters as long as they were formed according to the orthographic rules. For the non-characters a tendency to omit the left hand graphic component was also evidenced for the RH patient only. This separation of spatial framework and character reconstruction suggests that two different perception/production mechanisms are responsible for these types of data. Results of their copying responses are presented in Figure 2.

4. In the case of spontaneous drawing, the LH patient had no difficulty in following instructions, whereas the RH patient, once again, showed typical signs of visual neglect in the left visual field. Samples of their respective drawings are presented in Figure 3.
5. With regard to writing characters in order to give names to pictures depicted in the booklet, the RH patient showed no deficit in his performance. However, the LH patient made many omissions, as well as commission errors. The latter usually involved deleting parts of a character while maintaining the orthographic structure of the original character. Samples of their respective writings are presented in Figure 4

Figure 1 Samples of copies by the RH (right column) and LH (left column) patients according to models (center).

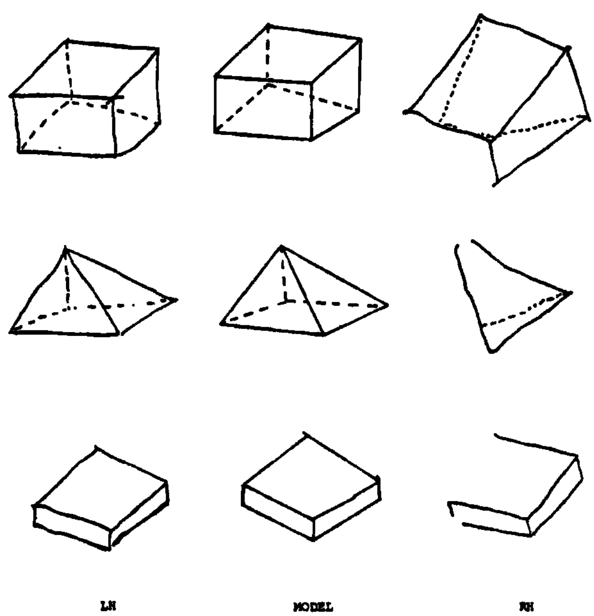
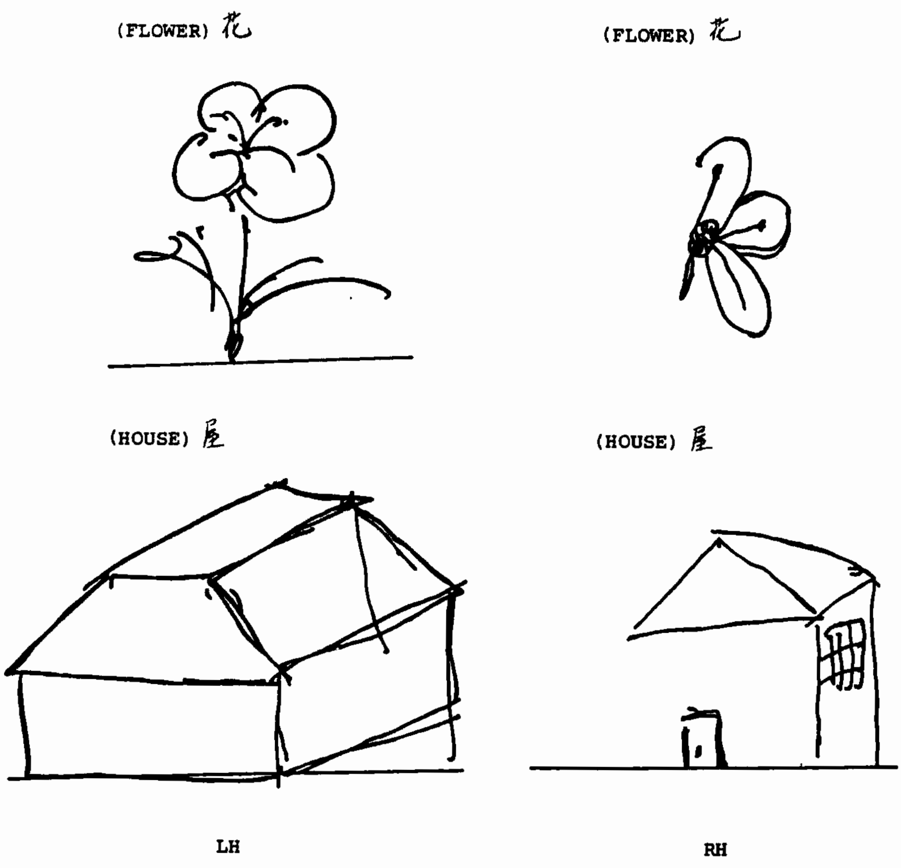
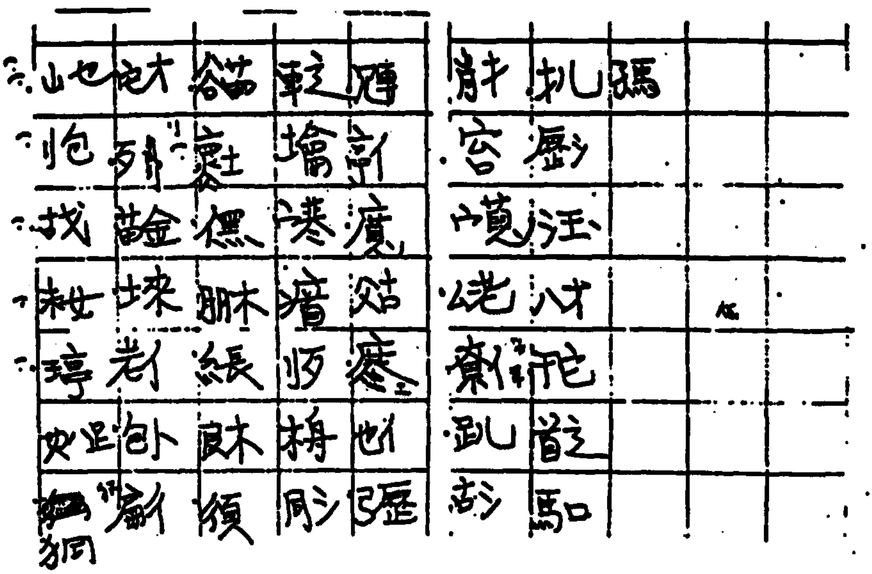


Figure 2 Samples of spontaneous drawings by RH and LH patients.



These results point to a definite conclusion: Chinese characters are not processed in any picture-like fashion. Instead, they are linguistic symbols which can be manipulated at different levels of abstraction, just like words transcribed by alphabetic letters. Most importantly, these data as a whole suggest that it is the left hemisphere, not the right hemisphere, which plays a dominant role in the writing of Chinese characters. The RH damaged patient showed typical signs of visual neglect in the left visual field, but in writing or copying characters the patient never missed any component-graph on the left hand side of a character. The separation of pictures and characters is most obvious, and as Bradshaw and Nettleton (1983) succinctly wrote, "... there is as yet no reported evidence of a selected impairment of Kanji processing consequent on right hemisphere lesion alone." (p. 152)

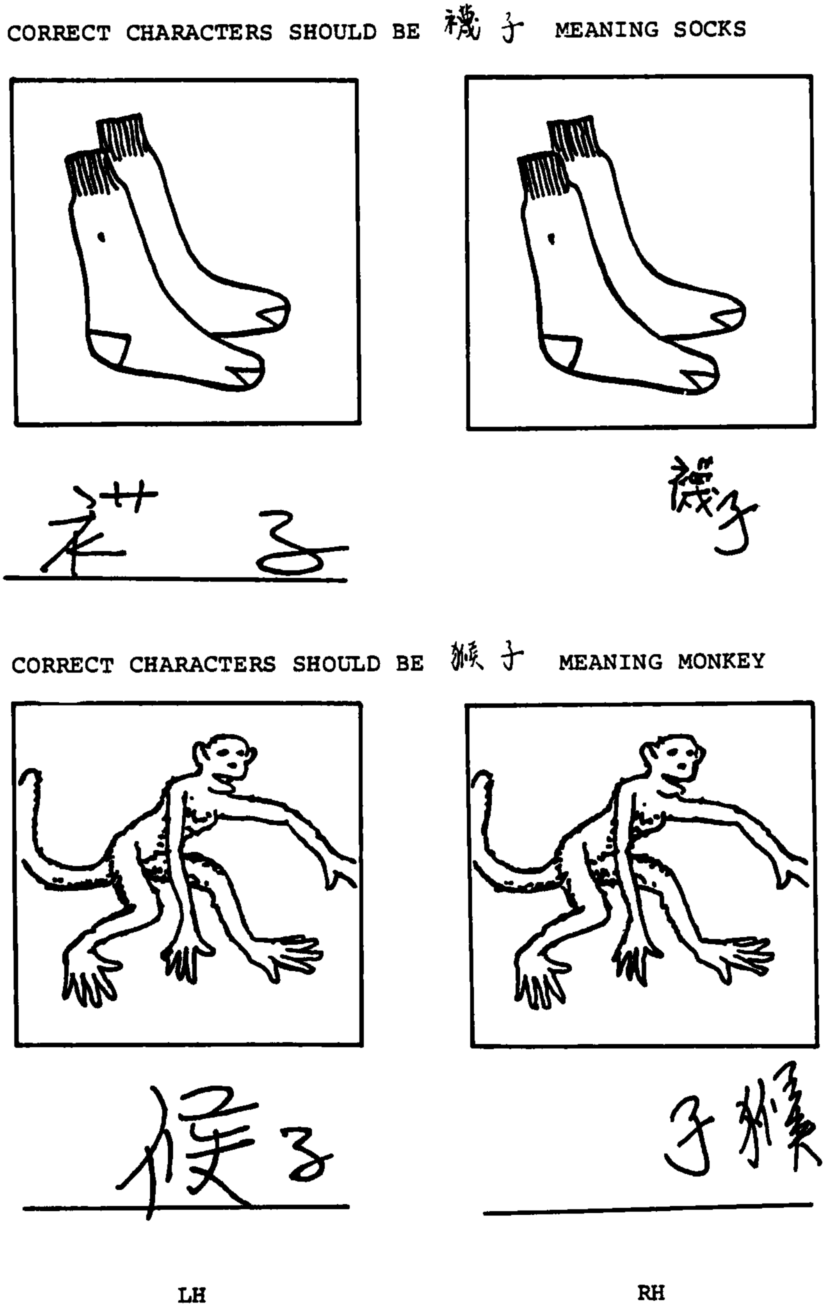
Figure 3 Samples of copying pseudo-characters onto a 7×10 matrix by the RH and LH patients.



LH

RH

Figure 4 Samples of spontaneous writings of object names by the RH and LH patients. Note that the RH patient's writings are correct while the LH patient's writings show missing parts.



GRAPHOMOTORIC CODES IN THE RECOGNITION OF CHINESE CHARACTERS

We have already noted that written languages not only differ in the degree of their script-to-sound mapping, but also differ in how their orthographies make use of space: English letters are always written linearly from left to right, whereas in Chinese, strokes can be positioned to the left, right, top or bottom of one another. Hence, one may expect Chinese readers to show greater sensitivity to spatial layout and/or configurational relations among components of stroke patterns in processing Chinese characters. Based upon such surface information, one may want to conclude that Chinese characters are processed primarily by the right hemisphere. However, we have clearly demonstrated in the previous section that it is the left hemisphere, rather than the right, that plays a much more dominant role in processing the characters. The question now becomes: Why does this occur in the left hemisphere?

To answer the question, it may be useful for us to search for a common "neuro-cognitive" mechanism which seems to cut across the three S's of human communication (i.e., speech, script and sign languages). Tzeng and Wang (1984) have recently proposed a "time-keeping" mechanism in the left hemisphere and suggested that language lateralizes to the left hemisphere because its greater temporal resolution enables the realization of the unique feature of duality of patterning. Essentially, what has been proposed is a sequential strategy and one can easily see how this strategy can be used to expand the capacity of messages under a limited set of basic elements (for detailed arguments, see Tzeng & Wang, 1984). Since English words are written letter by letter in a linear array, a sequential strategy for their perception can be appreciated. An intriguing finding in recent years is that perception of Chinese characters may be equally constrained by such a sequential strategy.

A relevant study, concerning Japanese grade-school children, was recently reported by Mann (1984). Mann observed that while American good and poor readers showed no difference in memorizing nonsense figures, Japanese good and poor readers of the same age showed a significant difference. Moreover, their performance in memorizing these nonsense figures correlated with their ability to read Kanji (Chinese characters) but not with their ability to read Kana syllabaries. Mann concluded from her findings that there is a special graphomotoric coding scheme for reading Chinese characters.

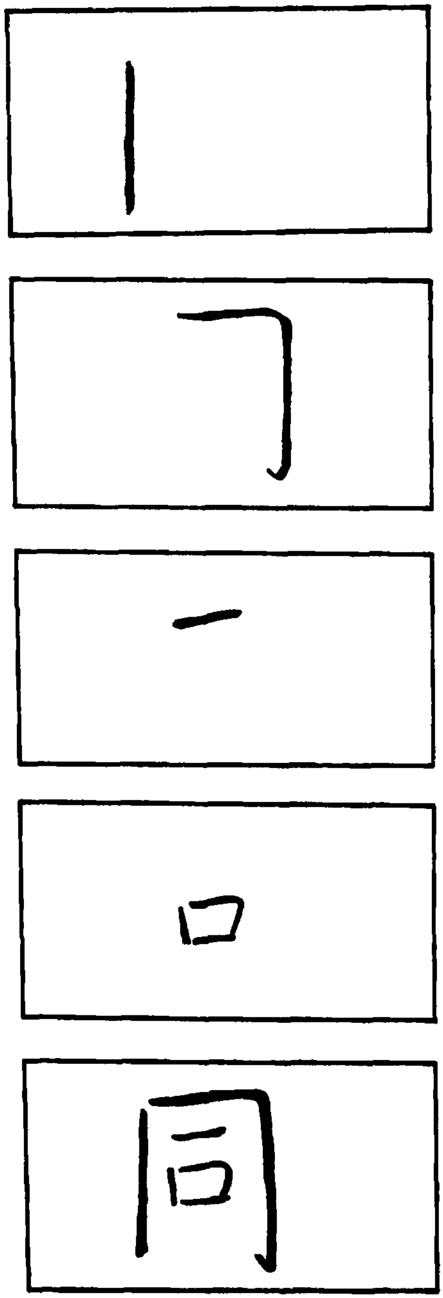
The proposal of the development of graphomotoric codes for the recognition of Chinese characters is also consistent with the observation that Chinese and Japanese alexic patients, when confronted with a character that they cannot read, will trace its strokes over and over again with their fingers as if trying to evoke a proprioceptive memory of writing it (Lyman, Kwan, & Chao, 1938; Sasanuma, 1980). We have confirmed such finger-tracing activities in our aphasic patients who have difficulty in reading Chinese characters, and we have further noted that these patients do not seem to look at what they are writing; in fact, some of our patients do not even know they are making the tracing movements until the act is specifically pointed out to them. These patients are attempting to reconstruct the configurational relations among component parts of a character. A global activity in tracing seems to provide the spatial frames upon which a character can be reconstructed. The reliance on the knowledge of stroke sequence to get access to the visual lexicon may be the underlying reason for the left hemisphere's dominance in processing Chinese characters.

We decided to study the nature of such tracing movements by employing a specific "visual gluing" experimental paradigm (cf., Huang, 1984). The procedure is rather straightforward. First, a Chinese character is broken down into various numbers of fragmentary pieces (but preserving the stroke-patterns). Second, the fragmentary pieces are presented one by one to the subject who is instructed to identify the character upon the offset of the presentation of the last piece. It has been noted that with this procedure, most subjects increase, consciously or unconsciously, the activity of figure tracing. Of particular interest is whether the subject's character identification performance will drop when his/her tracing activity is specifically prohibited.

We were also interested in comparing the visual-glue performance among different types of brain-damaged patients. In a previous study reported by Wu (1985) on the analysis of writing errors by Chinese aphasic patients, it was found that nonfluent aphasics tended to add additional strokes to a character, whereas fluent aphasics, especially those with damage involving the parietal area, tended to delete stroke patterns in either probed or spontaneous writing. In some pilot testing, it was also found that patients with left parietal damage seemed to be the most vulnerable to visual gluing tasks.

Twenty-eight high frequency Chinese characters of not more than nine strokes were selected from established norms in Taiwan (Liu & Chuang, 1971). They were broken down into 3–5 fragments according to their conventional writing sequences. Some examples are presented in Figure 1. Each fragmentary unit was drawn on a 3×5 index card within a 2.5 square inch space. Each component unit was carefully drawn in proportion to the whole character with respect to the spatial relations among all components. As can be seen from the examples provided in Figure 5, when one stacks the four stimulus cards and matches the central square, the whole character emerges. On each trial, the stimulus cards were presented to the patient one by one and then the patient was asked to identify the character that would emerge at the end of the last stimulus card. All patients went through eight practice trials before the real experimental trials began, ten with permission to do finger-tracing and the other ten with instruction not to trace with their fingers.

Figure 5 Sample cards used in the visual-glue experiment. The first four cards preserve stroke sequence and the last card shows the character (meaning "same" or "together") to be identified.



Six inpatients under neurology treatment at the Chang Gung Memorial Hospital and the National Taiwan University Medical Center were recruited for the visual-glue experiment. All patients underwent computed tomographic (CT) scanning of the head at the time that they were admitted to the clinic. Based on the CT results, two patients were identified as subjects with right hemisphere lesions, two were identified as having left-frontal lesions and the last two were identified as having left-posterior lesions. The case histories of these six patients are presented in Table 3.

Table 3 Case histories of the six patients in the visual-glue experiment.

Case	1	2	3	4	5	6
Age	55	60	58	31	58	36
Sex	M	M	M	M	M	M
Handedness	R	R	R	R	R	R
Native Language	Mandarin	Mandarin	Mandarin	Taiwanese	Taiwanese	Taiwanese
Years of Educ.	12	9	12	12	16	16
Occupation	Teacher	Officer	Soldier	Businessman	Engineer	Manager
Etiology	CVA	CVA	CVA	Head Injury	CVA	AVM
CT Scan	RH Basal ggl. infarct	RH infarct caudate necli	LH infarct Basal ggl.	LH Frontal compression	LH parietal infarct	LH Hemo. parietal posterial temporal
Neurological Information	Left hemiplegia	Left hemiplegia	Right hemiplegia	No defect	No defect	No defect
Speech Diagnosis	Normal	Normal	Mild Dysar.	Broca's aphasia apraxia	Conduction aphasia, agraphia Gerstmann	Nominal aphasia, agraphia

Results of performance on the visual-glue experiment by these six patients are summarized in Table 4 as a function of the location of brain lesion. Each patient has two entry figures which represent the percentage of correct identification without (first number on the left) or with finger tracing.

Again the results are quite clear in their implication that the left hemisphere plays a critical role in processing characters. With or without finger tracing the two RH damaged patients were able to mentally glue various pieces together to make almost perfect character identification in their "mind's eye." In contrast, all four LH damaged patients had tremendous difficulty in the gluing task, even with finger-tracing. These findings are consistent with our observations made in the writing study.

Table 4 Percent correct identification of stimulus characters as a function of with (in parenthesis) or without finger tracing.

	RH	LH	
Case #		Anterior	Posterior
1	100% (100%)		
2	90% (100%)		
3		70% (75%)	
4		50% (60%)	
5			0 (25%)
6			0 (10%)

Finger-tracing activity also had differential effects on the two types of lesions in the left hemisphere. For the two anterior patients, tracing did help, but not by much, whereas, without the help of tracing, the identification ability of the two parietal patients was essentially nil.

In sum, results of this visual-glue experiment support the proposal of a graphomotoric code in the recognition of Chinese characters. They show that by activating the motor pathway, albeit in a very loose manner, performance of character recognition by the LH damaged patient is greatly improved. This particular result is consistent with the observation in the western world on the reading performance by a type of patient with a reading disorder identified as word-form dyslexia (Warrington & Shallice, 1980) or letter-by-letter reading (Patterson & Kay, 1982; Coltheart, 1983). In this type of patients, who usually suffer from unilateral posterior left-hemisphere lesions, reading may be practically abolished. However, some reading can be recovered with a strategy in which the patient *explicitly* and *sequentially* identifies each letter of the word and then recognizes the word from this series of letter identities. That the recognition of Chinese characters can proceed in a similar fashion has profound implications for both theories of pattern recognition and neurolinguistics.

CONCLUDING REMARKS

It was more than one hundred years ago that Broca made his famous announcement, "We speak with our left hemisphere." (Broca, 1861). Then came the discoveries of various types of reading and writing disorders which were the consequences of left hemispheric lesions (Damasio, 1983). It seemed clear that the left hemisphere is functionally responsible for both primary and secondary languages. The spilt-brain research in the 70's added much supporting evidence for the idea of a mute right hemisphere (Gazzaniga, 1983). However, knowing that the right hemisphere must, in some important way, make complementary contributions to the possibility of the general language function, investigators have never stopped looking for some form of language processing, no matter how primitive, in the right hemisphere (Zaidel, 1983). While the debates for or against right hemisphere language processing continue (Gazzaniga, 1983; Levy, 1983; Zaidel, 1983), the idea that a visible language, such as written material, or, for that matter, the perception of sign language, might have a better chance of manifestation in the right hemisphere gives some researchers impetus to keep searching for the right hemisphere's linguistic ability.

Not surprisingly, when visual hemi-field experiments with a tachistoscopic recognition paradigm produced occasional and minimal evidence for a left visual field superiority in recognizing Chinese characters (or Japanese Kanji), many people got excited and quickly jumped to the conclusion that these characters must have been represented in the right hemisphere. Hasuike, et al. (in press) reviewed most, if not all, of the visual field studies and pointed out that there were, in fact, more studies that showed the right visual field advantage than those that showed the opposite result. Even for those few studies that did show a left field advantage, the effect was better accounted for by nonlinguistic factors such as low spatial resolution due to the administration of a very short exposure duration.

The results of comparing the performance of patients with right and left hemisphere lesions on writing and picture drawing tasks, as reported in the first study, should provide unequivocal evidence against the proposition that because of its picture-like characteristics, the Chinese script is represented in the right hemisphere by its readers. After all, Chinese characters are not picture-like in the sense of iconicity. They are essentially linguistic symbols which require verbal awareness for their processing, just like a string of speech signals which requires the same verbal awareness for its comprehension. And evidence is strong that verbal awareness seems to be a property of our left hemisphere (Gazzaniga, 1983).

Another possible reason that supports left hemispheric processing of Chinese characters is that a sequential frame for the graphomotoric codes representing various parts of a character may be better served by a "time-keeping" mechanism in the left hemisphere, as suggested by Tzeng and Wang (1984). The idea that the left hemisphere is more powerful for temporal resolution has been suggested (Levy, 1984; Tzeng & Wang, 1984; among others) and empirical evidence has been gathered from both experimental as well as clinical studies (Hammond, 1981; Kimura, 1979; Ojemann & Mateer, 1980). Results from the visual-glue experiments mentioned above provide indirect support for the sequential hypothesis.

Looking at our data from such a perspective, two intriguing observations deserve further comment. First, it is clear from the limited set of data reported here that with respect to the gluing task patients with posterior lesions perform much worse than those with anterior lesions. It is almost tempting for us to suggest that somewhere in the parietal area and adjacent to the visual cortex, there may lie an area which provides a graphomotoric schema for integrating (or conjoining in Treisman's sense of visual attention) features into a recognizable character; its function is probably parallel to that of Broca's area with respect to the articulatory program. More experiments are definitely needed to specify the nature of its function, especially with respect to basic processes in writing and reading.

Second, we believe that the data presented here, together with the critical review done by Hasuike, et al. (in press), demonstrates beyond a doubt that Chinese logographs are processed mainly in the left hemisphere. This is not to say that the right hemisphere makes no contribution for their perception. Of course, it does contribute and continues to do so throughout the entire process of reading. What we are arguing is that words written in an alphabetic script require the dominant left-hemisphere's verbal awareness for their perception and production. So do words written in logographic script. We think it is time for scientists to base their judgments on empirical data such as what we have presented here, rather than on wild speculations and on naive views of orthographic structures.

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Society for the Science and Technology of Handwriting and Other Graphic Skills

An Introduction

The recent past has seen the rapidly growing interest in the research of the handwriting process. This interest is shared by experimental psychologists, cognitive scientists, educationalists, letter designers, forensic psychologists, neurologists, neuropsychologists, biophysicists, researchers in artificial intelligence and engineers involved in the analysis of handwriting trajectories and in procedures for the automatic recognition of handwriting. This multifaceted and multidisciplinary research interest is denoted by the single term *'graphonomics'* which was coined a few years ago. The label graphonomics intends to convey the connotation of scientific effort concerned with the systematic relationships involved in the generation and analysis of the handwriting and drawing movements, and the resulting traces of writing and drawing instruments, either on conventional media such as paper and blackboard, or on electronic equipment. As such, graphonomics does not encompass the research of keyboard skills. Obviously, graphonomics has many subdisciplines, both pure and applied, as we shall see below. As a scientific enterprise, graphonomics is clearly distinct from the art of graphology. The severity of the latter distinction is somewhat uncertain. At present it can be said that the graphonomics-graphology distinction probably occupies an intermediate position with the psychonomics — psychology distinction (between two highly compatible aspects of the same discipline) on the one side and the extreme astronomy-astrology distinction (between an advanced science and popular occultism) on the other.

Handwriting has always been able to arouse a great deal of interest, but scientific endeavours remained very limited in scope and the results generally were not suited to serve any practical purposes. Two reasons for this situation were that sound theory to guide research was lacking on the one hand, and that facilities for the analysis of the writing process were restricted to simple timing and pressure measures. Indeed, much of the research on handwriting was often concerned with the finished writing product rather than with the writing process. The developments over the past decades, both in human performance theory including theories of action and motor control, and in electronic hardware and computer software, by means of which the writing trace as well as its dynamic genesis can be analyzed in great detail, have given rise to the renewed interest in handwriting. Moreover, the computer age also gave an impetus to the community of investigators from various disciplines to approach also motoric organization ('motor knowledge') including handwriting and drawing in computational terms. Furthermore, neurologists have come to recognize handwriting as a specific skill which reveals aspects of linguistic as well as motoric structures and related strategies similar, but not identical, to those of speech. In addition, psycholinguists who have had some success in revealing important aspects of speech production and of the recognition of spoken and printed language, are now becoming interested in models of the two remaining forms of language processing, viz., typing and handwriting.

In the footsteps of these speech and language technologists, joint efforts are now being undertaken by human performance scientists and engineers to arrive at the degree of insight into handwriting that will permit handwriting production by a simulator as well as the automatic reading of handwriting based on this insight in an analysis-by-synthesis fashion. On the applied side, the reading of handwriting by computer will add a further natural communication mode with our electronic equipment. The next generation of computers and software will indeed be characterized by very high-level languages and by very sophisticated user interfaces. Powerful man-machine communication techniques involving speech and handwriting recognition will be incorporated into these systems. Computers will be designed to understand handwriting either off-line via optical character readers and cameras, or on-line via digitizers or instrumented pens. Furthermore, knowledge of the handwriting process should provide solutions to these highly complex pattern recognition and verification problems.

Moreover, with the development of various new curricula in the primary school, many have expressed the need for improved methods for teaching handwriting and for the use of 'natural' letter shapes. Some instructors claim, for example, that the curriculum should be based on better knowledge of the process of handwriting in order to deal with the learning problems related to the developing skill and to cope with differences in handedness and variations in pen grip. Still a further practical area where there is a need for a large amount of sophistication with respect to the handwriting process is that of the forensic investigation of handwriting. In this field, questions that are frequently asked concern the discriminative power of trajectory features and the automatic classification of a specimen of handwriting according to these features. Applied questions such as these, however, may have to wait for answers to be provided by the achievements in the above more fundamental areas.

Obviously, the present interest in the science and technology of handwriting is both multidisciplinary and interdisciplinary in nature. 'Approaches to movement in graphic behaviour' are simultaneously being made from many different directions, sometimes independently, sometimes as a joint effort. But for its ultimate achievements, every approach is partly dependent upon the results obtained in one or more other directions. Researchers in the field of graphonomics have felt this mutual dependence for some years now. To encourage multidisciplinary contacts and interdisciplinary cooperation, the first Symposium on the Motor Aspects of Handwriting was held in 1982 at the Department of Experimental Psychology of the University of Nijmegen, The Netherlands. The proceedings of that Symposium appeared as a special volume of *Acta Psychology* (Vol. 54) in 1983, followed by a separate book (A.J.W.M. Thomassen, P.J.G. Keuss, & G.P. van Galen (Eds.) *Motor aspects of handwriting: Approaches to movement in graphic behavior*. Amsterdam: North-Holland, 1984). Because of the enthusiasm generated at this first meeting, it was judged desirable to continue the inter-and multidisciplinary orientation and organize a further Symposium after a few years. The Second Symposium on the Neural and Motor Aspects of Handwriting was held at the Department of Psychology, the University of Hong Kong, in July 1985. Its proceedings constitute the present volume in the series Advances in Psychology.

During the 1985 Symposium the decision was made to establish the International Graphonomics Society (IGS) to promote the inter-and multidisciplinary research and technology of handwriting and other graphic skills. To achieve these goals, the Society will act as a permanent body to provide and transmit information on all aspects of graphic behaviour and at the same time to initiate contacts with both 'pure' and 'applied' researchers in other related disciplines and in various organizations. The information collected by the Society will appear in issues of the IGS Bulletin, which will be sent to members of the Society in March and October each year. The IGS Bulletin will also contain information on relevant conferences and workshops, on reports and publications produced by its members, on vacancies, training programs, Ph.D. positions, as well as on instrumentation and other facilities. Furthermore, the IGS will be responsible for organizing further symposia, for accepting contributions to these symposia, and for publishing the proceedings of the symposia. Although the recent second Symposium was organized before the Society was actually established, the IGS gladly takes responsibility for the present proceedings of that conference, which even carry the graphonomics label in their title. Finally, the Society may act as an intermediary in establishing contacts between organizations defining research questions and individuals or groups best suited to perform specific types of research or to develop required instruments and software. In future years, of course, the IGS might grow to a point where it will become difficult for its members to maintain active contact with the entire field. In this case, subdivisions could be established in areas such as Motor behaviour, Recognition, Forensic science, Educational research and Neuropsychology of handwriting. If this occurs, sections devoted to these subdivisions will naturally appear in future issues of the IGS Bulletin. It is also quite feasible that members of each of these divisions or 'disciplines' might organize workshops under the auspices of the IGS. It should be stated explicitly that the IGS does not intend to operate in competition with any existing organizations or groups in the area of handwriting and drawing, either at the national level (such as the Handwriting Interest Group in the United Kingdom) or at the international level (such as the Association Typographique Internationale — ATypI). Instead, the IGS aims at close contacts and cooperation so that the activities will be mutually inspiring and complementary rather than competing.

The establishment of the IGS in 1985 was accompanied by the installation of a Board whose members are charged with helping the Society to reach its goals. These members are: Henry S.R. Kao, Hong Kong; Pietro Morasso, Genova, Italy; Marvin Simner, London, Ontario, Canada; Nils Søvik, Trondheim, Norway; George E. Stelmach, Madison, Wisconsin, U.S.A.; Arnold J.W.M. Thomassen, Nijmegen, The Netherlands (President); Alan Wing, Cambridge, U.K.; Xu Liancang, Beijing, China.

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SUBJECT INDEX