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A study of handwriting production

Educational and developmental aspects

Ruud Meulenbroek

**A study of handwriting production:
Educational and developmental aspects**

A study of handwriting production

Educational and developmental aspects

*Een wetenschappelijke proeve op het gebied
van de Sociale Wetenschappen*

Proefschrift

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aan de Katholieke Universiteit te Nijmegen,
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More than 100 pupils of two primary schools in Nijmegen (*De Lanteeerne* and *De Carillon*) participated enthusiastically in three experiments. The repetitive nature of the writing tasks sometimes placed high demands on their perseverance. Over a period of more than a year, the team of *De Lanteeerne* paid special attention to the skill of handwriting. During this period I was able to observe the handwriting performance of many children within the classroom several times. I also participated in stimulating teaching-staff meetings in which the teachers discussed the implementation of various scientific insights of handwriting production in their classrooms. The evaluation of these attempts was very informative. The headmaster, Joop Haverkort, as well as the teachers deserve special thanks. I also thank Alger Hagen of the *School Advies Dienst Nijmegen*, who introduced me to the primary schools mentioned and who assisted me in some applied aspects of the research project.

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Chapter 1

Introduction

SETTING THE FRAMEWORK OF THE STUDY

The present thesis reports a series of empirical investigations on the production of handwriting movements. The studies are concerned with a set of handwriting tasks which successively increase in complexity. Moreover, the tasks are selected to be educationally relevant. Indeed, the main aim of this thesis is to contribute to the improvement of formal handwriting education. Even in these days of sophisticated electronic typewriters and word processors, handwriting is still an important language skill deserving thorough investigation. Taking notes and writing personal letters are just two examples of inconspicuous, yet important communication tasks. Handwriting is even more important in educational settings. On the one hand, pupils must be able to write down information offered to them, and on the other hand, they often have to convey their own knowledge by means of handwriting. As a language skill, handwriting is closely related to other important and complex skills such as reading and speaking, not only with regard to the cognitive components underlying their performance (Ellis 1984; Margolin 1984) but also with regard to their common communicative function.

Handwriting as studied in the present thesis must be distinguished from writing insofar as manipulating a writing tool by means of arm, hand and finger movements is essential in the former task, whereas the generation of ideas and their expression in accordance with syntactical and lexical rules are the essence of the latter task. It must also be recognized that handwriting is not a natural skill, i.e., that it is highly culturally dependent, that it has to be learned in a relatively short period during which profound refinements of the cognitive, perceptual and motor system take place, and, that its products must be legible in order to serve its communicative function. For these reasons it is generally recognized that handwriting has to be instructed and trained in formal education.

Reviews of educationally oriented research on handwriting in the 1960s and 1970s (Askov, Otto & Askov 1970; Peck, Askov & Fairchild 1980) show that a large number of experiments were directed at a variety of aspects of the task. Askov et al., and Peck et al., conveniently followed the suggestion made by Herrick and Okada (1963) to organize educationally oriented handwriting-research following seven research topics. In the 1960s and 1970s the majority of the studies were directed at: (1) the investigation of the nature of letter forms most efficiently and legibly produced; (2) instructional techniques and correlates of skill development in handwriting; (3) the effects of various body-part positions on writing performance; (4) the effects of speed and stress on the handwriting product; (5) the effects of

instructional sequences on the development of handwriting skills; (6) the nature of handwriting instruments and writing surfaces facilitating learning to write, and finally; (7) the development of improved handwriting evaluation scales.

An overview of the educationally oriented studies during the current decade (see Table 1) shows that research into the majority of these topics has continued also in the 1980s. However, it appears from our table that most of the recent studies on educational aspects of handwriting were concerned with the second topic, viz., instructional techniques and correlates of skill development.

The experiments to be reported in the present thesis are concerned with the first four and the sixth of the abovementioned topics. To name a few examples, effects of speed-accuracy instructions on the quality of the stroke-production process, factors determining the fluency of letter formation, and correlates of skill development are investigated. Although the thesis is also educationally oriented, the organization of its research differs from the one suggested by Herrick and Okada (1963). In order to discuss these differences, an outline of the global organization of the present thesis is required.

Subsequent to the present chapter, six chapters will follow in which six experiments will be reported. Chapter 2 presents a laboratory experiment concerning the production of simple line drawings by adults. We consider the line-drawing task as a precursor of the handwriting skill. Chapter 2 outlines the theoretical background of the thesis. It investigates an information-processing model of complex motor behaviour originally developed by Van Galen (1980) in the context of handwriting. The model describes the psychomotoric components underlying the production of drawing and handwriting movements. Another important aspect of the second chapter is the introduction of the research technique which is used in the subsequent chapters. This technique consists of the digital recording of penpoint movements and analyzing these recordings with a high degree of precision (Teulings & Maarse 1984).

Following this first study, we leave the laboratory and enter the field of education to report four experimental studies conducted in the setting of two primary schools. These studies investigate the handwriting movements of primary-school children producing simple stroke sequences, single cursive letter forms and cursive bigrams. The order of these tasks corresponds closely to the order in which children are taught the skill of cursive handwriting. The nature of our successive research questions changes correspondingly. At the start they are predominantly concerned with peripheral aspects of handwriting. Subsequently they increasingly pertain to

Table 1

Educationally oriented research on handwriting in the 1980s organized following the seven research topics described by Herrick & Okada (1963)

Authors	Research topic						
	1	2	3	4	5	6	7
Jackson, Jolly & Hamilton (1980)		x					
Wright & Wright (1980)		x					
Søvik (1981)		x					
Waggoner, LaNunziata, Hill & Cooper (1981)		x					
Hayes (1982)		x					x
Hill, Gladden, Porter & Cooper (1982)							x
Lally (1982)		x					
Søvik & Teulings (1983)		x					
Trap-porter, Gladden, Hill & Cooper (1983)		x					
Burkhalter & Wright (1984)		x					
Sims & Weisberg (1984)		x					
Søvik (1984)		x					
Ziviani (1984)		x					
Armitage & Ratzlaff (1985)		x					
McKay & Neale (1985)							x
Phelps, Stempel & Speck (1985)							x
Ball (1986)		x					
Feder (1986)		x					
Graham (1986)							x
Koenke (1986)		x					
Ratzlaff & Armitage (1986)		x					
Sassoon, Nimmo-Smith & Wing (1986)					x		
Ziviani (1986)					x		
Blandford & Lloyd (1987)		x					
Stott, Henderson & Moves (1987)		x					
Wood, Webster & Gullickson (1987)		x					
Blöte (1988)					x		

central aspects of the skill. The control of simple hand and finger movements is investigated first. This is followed by a search for the factors determining the perceptual and motoric complexity of letter forms. Finally, the requirement of coordinating the production of two joined letters is examined. In studying the handwriting movements of school children, special attention is given to developmental aspects. Age-related changes in movement-control strategies are inferred from the recorded handwriting movements. These changes are verified in three of the four experiments conducted with primary-school children, and they are related to other

empirical findings in the literature concerning the development of grasping and reaching.

The series ends with a final laboratory study focussing on the written production of words by adults. The experiment was designed to investigate variations in handwriting performance as a function of the important subject variables of handedness, hand posture, and gender. Writing with the left hand is a specific matter of concern for teachers and educationalists. We argued that left-handed writing may well be studied in adult subjects because these subjects, having years of writing experience subsequent to their formal writing education, may be expected to have developed consistent, more or less efficient movement strategies. An analysis of these strategies should yield useful insights for the design of training situations for left-handed children.

The thesis is concluded with a chapter which consists of an epilogue discussing the application of fundamental insights in handwriting to the field of education. The implications of a recent theoretical model of handwriting production (Van Galen, Meulenbroek & Hylkema 1986; Van Galen, Smyth, Meulenbroek & Hylkema, in press) for the organization and the content of a handwriting curriculum are discussed. Subsequently, an attempt is made to exploit the empirical findings of the present series of experiments, as well as the research technique with which their data were collected and analyzed, in the applied settings of formal writing education and the treatment of writing problems.

Having described the global organization of the thesis we are now able to indicate how the present experiments differ from the educationally oriented studies of handwriting mentioned previously. In the present experiments we make use of sophisticated computer techniques to record and analyze both the spatial and kinematic aspects of handwriting movements with great precision, whereas the earlier studies were generally aimed at the handwriting products to evaluate performance. In order to evaluate these finished products, researchers mainly relied on subjective judgement in which techniques such as error classification, observation by means of transparent overlays, and the employment of assessment scales play a central role. In contrast to these studies, the present thesis may be characterized as a study of handwriting movement instead of a study of handwriting products. Furthermore, we claim that the systematic analysis of the kinematics of handwriting movements enables us to make inferences about the underlying psychomotoric processes and their development. In our view, these processes determine to a relatively high degree the actual handwriting performance (Van Galen 1980; Van Galen & Teulings 1983; Van Galen et al. 1986; Van

Galen et al., in press; Teulings 1988). The present line of research may therefore be characterized as process oriented rather than product oriented.

As far as our theoretical approach and research technique are concerned, our study is strongly associated with various other recent studies focussing on the analysis of handwriting movements (Dooijes 1984), the development of peripheral models of handwriting (Maarse 1987), and - most strongly - with the development of central models of handwriting (Teulings 1988). With regard to the educational and developmental aspects, our study is closely related to the studies by Wann (1986; 1987) and Wann & Jones (1986) who were able to differentiate primary-school children displaying advanced or retarded handwriting acquisition by means of kinematic analyses of digitally recorded handwriting movements.

The inference of psychomotoric and developmental processes from analyses of detailed recordings of task performance has a long history in experimental psychology and it deserves to be discussed at the outset of this thesis.

A wide range of motoric skills has been investigated either from an information-processing viewpoint which attempts to decompose skills into the subprocesses of perception, recognition, response planning, motor programming and motor adjustment, or within an ecologically oriented theoretical framework which emphasizes the direct relationship between changes in the immediate environment and changes in behaviour of the subject. Speech production (Sternberg, Monsell, Knoll & Wright 1978), typing (Shaffer 1978; Rumelhart & Norman 1982), piano playing (Shaffer 1980), sending morse codes (Klapp & Rodriguez 1982), and juggling (Beek 1988) are but a few interesting examples of such skills. Skills in which vision directly influences performance are often studied within an ecological theoretical framework where researchers refrain from using assumptions concerning the existence of internal representations of invariant aspects of task performance. Concepts like coordinative structures and muscle linkages are used to describe rather than to explain the direct link between vision and action (Turvey 1977; Turvey, Shaw & Mace 1978). The ecological approach, however, has not yet been able to explain sufficiently the permanent changes of skilled motor behaviour occurring as a result of growth and learning, whereas the information-processing approach has demonstrated considerable explanatory power with regard to these aspects (Schmidt 1987; Sheridan 1988). Skills which are relatively independent of visual or other forms of afferent input (e.g., typing, piano playing, producing morse-codes) are often studied from the viewpoint of information processing. This approach assumes that during practice, sensory information (visual, kinaesthetic,

tactile) is used for the evaluation of motor performance. This evaluation of task performance on the basis of information from various senses is supposed to be necessary for the build-up of internal representations which contain essential information regarding task performance. It is assumed that these representations initiate and shape future actions. The information-processing approach uses constructs such as feedback, schemata, motor programmes and open and closed-loop motor-control mechanisms, not only to explain skilled behaviour, but also to describe changes in skilled behaviour as a result of learning and development (Adams 1971, 1976, 1984; Keele & Summers 1976; Keele 1981, 1982; Schmidt 1975, 1976, 1982; Summers 1980; Stelmach & Diggles 1982).

Handwriting can be characterized as a task in which vision is relatively unimportant, at least as far as skilled writers are concerned (Van Galen et al., in press). A skilled writer generally uses visual information only to monitor his or her performance mainly at the level of words. He or she visually checks the global consistency with which the words are placed along the lines of writing. The visual control of the production of individual letters is largely restricted to the letters containing stroke repetitions, viz., the letters *n*, *m*, *v* and *w*. There seems to be no direct link between visual information and the production of individual upstrokes and downstrokes. A skilled writer produces a single stroke in about a tenth of a second and visual information cannot interrupt the production of the stroke once it is initiated (Teulings 1988). Because skilled handwriters rely on internal information to produce, control and coordinate handwriting movements, we argue that the information-processing approach is more suited than the ecological approach to describe and explain cursive-handwriting production.

The information-processing approach was strongly boosted by Sternberg's additive-factor method for analyzing choice-reaction times and his studies on speech and typewriting (Sternberg 1969; 1978). By analyzing the combined effects of two or more task variables on choice-reaction time, Sternberg showed that task performance could be decomposed into perceptual, decisional and motoric subprocesses. Sanders (1980), reviewing a large number of experiments using the additive-factor method, showed that relatively little attention had been paid to subprocesses at the motor side of the reaction process. The first experiment of this thesis has a bearing on this latter aspect. It shows that when subjects perform a simple drawing task in a laboratory situation in which they are pressed to perform line drawings rapidly and accurately, three motoric task variables independently determine the variations in choice-reaction time. According to the additive-factor logic, this indicates the presence of three independent stages in the information-processing sequence. Together with comparable findings in other choice-

reaction time experiments concerning handwriting tasks, the results of the first experiment are thus considered as confirmative evidence for a three-stage model of the production of handwriting movements. This model is discussed extensively in chapter 2. Linear stage models of human task performance assume that only one subprocess is active at any one moment and that the amount of time taken by one subprocess does not influence the amount of time required by another subprocess. These assumptions have been criticized, e.g., by McClelland (1979), McClelland and Rumelhart (1981), Rumelhart and McClelland (1982) and Turvey (1973). These authors presented experimental results which challenged the assumptions underlying the so-called discrete stage models. As a consequence, models of concurrent processing appeared. At present, much attention is paid to the distinction between linear and concurrent processing models of skilled behaviour (e.g., Miller 1988).

Recently, a mixed linear and parallel information processing model of handwriting production has been developed by Van Galen, Meulenbroek & Hylkema (1986) and Van Galen, Smyth, Meulenbroek & Hylkema (in press). Although the model is not explicitly investigated in the present thesis, it has influenced the research questions and hypotheses of the present series of experiments, the order in which the experiments were performed, and the evaluations of the results to be discussed in the following chapters. Furthermore, the epilogue indicates some of the implications of the model for the field of handwriting education. Because of the strong applicability of the model to our research questions and the organization of handwriting curricula, we describe the model at this point of the introduction. We will discuss the information-processing levels distinguished by the model and the presumed transformation processes occurring at these levels. This description of the model is followed by a more detailed introduction to each of the chapters of this thesis in order to point out how the model has influenced the research questions, hypotheses and evaluations of the results of the present series of experiments.

The model distinguishes six different information-processing levels at which the representations of increasingly smaller handwriting units are processed during real-time production. With regard to the handwriting units, the model distinguishes words, letters, and strokes. Word-units are represented by (1) phonological and (2) grapheme-sequence representations. Letter-units are represented by (3) allographic representations and (4) motor programs, and finally, stroke-units are represented by (5) the motoric representations of movement parameters and (6) muscle groups. These representations become accessible for information processing in a fixed

order, each representation at its appropriate level. The model uses the hypothetical construct of a 'memory buffer' to explain the temporal characteristics of the information flow between the successive information-processing levels. The output of an information-processing level is, according to the model, temporarily stored in a memory buffer until the information is retrieved for further processing at a subsequent level. The information processes occurring at the six levels can be characterized as follows. It is assumed that semantic and syntactical rules have determined the moment at which a word has to be produced in the context of other words of a phrase, or sentence. At this point the orthography, or the spelling of the word has to be produced. The necessary processing occurs on a supposedly phonological representation of the word according to lexical and/or phoneme-grapheme conversion rules. The result is a representation of the appropriate grapheme sequence (cf. Caramazza, Miceli & Villa 1986). The latter sequence is processed next. This processing leads to a sequence of allographs. An allograph can be defined as one of the possible forms of a grapheme. For example, depending on the position of a word within a sentence and the position of a letter within a word, a grapheme can eventually appear as either an upper-case or a lower-case allograph. The specific allograph is selected by the retrieval of its motor programme from motor memory. This programme is placed in a short-term motor buffer for further processing. The programme can be defined as an abstract representation of an allograph containing (1) spatial information about the stroke sequence and (2) dummy parameters for size and speed. Depending on the task requirements, the dummy parameters are set at specific values. Finally, the proper motor units are selected and activated in the motor system before the actual strokes are initiated by specific muscle groups. While these processes on the representations of a word, its letters, and strokes occur in a strictly hierarchical manner, the subject is, according to the model, capable of processing a second word at the same time, i.e., in parallel. This implies that the subject is ahead in time with regard to the preparation of subsequent handwriting units. The model can therefore be characterized as a mixed linear and parallel model of the production of words, letters and strokes in cursive handwriting.

It must be recognized that the model has been developed on the basis of empirical data obtained from adult subjects who may be considered as highly experienced writers. Since the present thesis is mainly concerned with the handwriting of primary-school children, the above hierarchical order from word to muscle activity may not be the most appropriate order to describe the psychomotoric components that have to be mastered by children. Indeed, the latter order is roughly the reverse of the former. First, children have to

acquire reasonable control of hand and finger movements. After having acquired this, they learn to perform simple stroke sequences. These repetitive writing patterns are generally performed under a wide range of size and speed conditions. Then - at least in Dutch schools - children learn to produce the lower-case allographs of the cursive alphabet. Finally they master the production of grapheme sequences representing words. It is this order which reflects the sequence of studies to be reported in the present thesis. In order to situate each experiment within the theoretical framework of the above mixed linear and parallel model of handwriting production, I will now introduce the next six chapters of this thesis in slightly more detail than was done earlier in the present chapter with a different purpose.

Chapter 2 presents an experiment in which adult subjects perform a line-drawing reaction-time task. Following the additive-factor method for the analysis of choice-reaction times (Sternberg 1969) the results verify earlier findings indicating that three independent information-processing stages can be identified at the motor side of the reaction process. These stages cover psychomotoric aspects of the production process of handwriting movements, viz., the central retrieval of abstract memory representations of handwriting units, the setting of actual parameters of size and speed, and the peripheral neuromuscular preparation of the anatomical systems involved. Furthermore, the experiment tries to localize the motor stage (or stages) at which variation of abstract motor preparation exerts its effect. This chapter is concerned with the three most peripheral information processing levels described in the model of Van Galen et al. (in press).

Chapter 3 reports an experiment in which 30 six- to eight-year-old children produce simple stroke sequences. In order to write repetitive sequences of upstrokes and downstrokes of various forms, children have to coordinate wrist and finger movements reasonably well. In the experiment, primary-school children write six different repetitive writing patterns in various speed/accuracy and lineation conditions. An analysis of the kinematic aspects of the production of upstrokes and downstrokes reveals factors determining the differential complexity of the patterns as well as differential effects of speed/accuracy and lineation conditions on movement production. The experiment can be situated at the two most peripheral levels of the model described above because it investigates the stroke-production process under various speed/accuracy conditions. The results of this experiment also indicate the presence of a discontinuous trend in kinematic variables as a function of age. This developmental trend in handwriting acquisition is investigated more thoroughly in the second experiment of chapter 4.

The first experiment of chapter 4, however, is concerned with the differential complexity of retrieving memory representations of handwriting units at the letter level, i.e., in terms of the presented model; at the allographic level. 75 eight- to twelve-year-old primary-school children write the individual letters of a cursive alphabet in a reaction-time task following the visual presentation of printed and cursive stimulus letters, respectively. Response-initiation times, velocity and dysfluency measures are investigated as a function of the letter-presentation mode (cursive or printed) and the different letters of the alphabet. A number of educationally relevant complexity factors of printed and cursive letters are revealed in this chapter.

The second experiment of chapter 4 investigates more thoroughly the discontinuous developmental trend, found in the first experiment. The data of the first experiment of chapter 4 are analyzed from a different viewpoint. Changes in movement time, distance, velocity, curvature and dysfluency in the production of strokes across age groups confirm the presence of a discontinuous developmental trend. By referring to the findings of Hay (1979, 1984) and Von Hofsten (1979, 1980), who demonstrated comparable developmental aspects in children's pointing and aiming movements, the results are discussed in terms of movement strategies which underly performance. In an early stage of skill acquisition, movements appear to be controlled by an open-loop movement strategy. Subsequently, performance is monitored and controlled on the basis of sensory information according to a closed-loop movement strategy. The latter strategy results in a temporary decline in performance. Finally, both movement strategies are integrated and skilled performance gradually appears.

Chapter 5 enters the level of digraphs, i.e., of the production of cursive letter pairs. It reports an experiment concerning the production of connecting strokes in cursive script. By extending the kinematic analysis used in chapters 2 to 4 to the spatial analysis of within-letter and between-letter upstrokes, it is established that the production of connecting strokes in cursive script constitutes a specific subskill of the cursive handwriting task. The experimental results are considered as confirmative evidence for the view that single allographs are produced on the basis of motor programmes, whereas the production of digraphs requires a separate computational process which controls the production of the connecting strokes between graphs. The experiment has to be located at the allographic level and the stroke level of the model of Van Galen et al. (in press). Furthermore, the discontinuous trend found in the kinematic aspects of within-letter stroke production in the former chapter is again observed in this chapter. However, a continuous developmental trend emerges in the kinematic aspects of between-letter strokes. These results are discussed once more by referring to the relation

between open and closed-loop movement strategies in handwriting acquisition.

Chapter 6 reports the final experiment of this thesis. Its main focus is on word production. The experiment is concerned with variations in cursive-handwriting production as a function of handedness, hand posture and gender in adult subjects. The experimental tasks consist of the production of repetitive writing tasks and of cursively written words of different lengths. The analysis is directed at kinematic aspects of stroke, letter and word production. The results of this experiment show only minor differences in stroke and letter production as a result of handedness, hand posture and gender. Systematic motoric differences between righthanders and lefthanders are mainly found in the number and distances of pen-lift movements made by the subjects during the production of words. It is suggested that the inverted hand posture used by most lefthanders can be considered as a functional adaptation to the global left-to-right direction along which the alphabetical orthographies have to be produced. With regard to the model of Van Galen et al. (in press) the experiment covers the levels of words, letters and strokes.

Chapter 7 concludes the dissertation and consists of an epilogue discussing some of the implications of the mixed linear and parallel model of handwriting production of Van Galen et al. (in press) on the organization and the contents of handwriting curricula. The linear, or hierarchical aspect of the model implies that handwriting curricula should provide a specific order of instructional techniques which guarantees that pupils learn to produce single handwriting strokes, under varying speed and accuracy conditions, and in specific movement directions. Subsequently, stroke combinations, letter forms, letter combinations and words have to be introduced. The parallel aspect of the model implies that the instructional techniques themselves should elicit preparational activities of the various handwriting units rather than copying or tracing activities which emphasize continuous eye-hand coordination during movement production. Subsequently, an attempt is made to make the empirical findings of the present thesis useful for handwriting education. Finally, a description is given of a computer-assisted environment for writing education which is especially relevant for the treatment of handwriting problems. In this situation a micro-computer presents the learning child with a handwriting task and records the writing movements during the performance of the task. The recordings are analyzed quickly and the kinematic and spatial aspects of the movements are evaluated. Almost immediately after finishing the task the child is given various types of feedback, e.g., about writing size, speed, pen pressure and fluency. The educational value of this specific training situation has not been determined in this thesis but comparable computer-assisted training situations concerning

handwriting have been developed and tested in the special educational settings for deaf (Brooks and Newell 1985) and blind (Macleod 1980) students. The effects of these training situations appear to be promising and deserve to be investigated in future research.

The chapters of this thesis have been published or will be published before long in journals and edited books (see Table 2). The research report of the first experiment of chapter 4 has been submitted for publication. Apart from a few minor corrections, the published chapters have been reprinted literally. The last three references concern two articles and a technical report of the Nijmegen Institute for Cognition Research and Information Technology (NICI) which formed the basis of chapter 7 of this thesis.

Table 2
Overview of published and submitted articles constituting
the substance of the present thesis

Chapters	Articles
Chapter 1	Van Galen, Meulenbroek & Hylkema (1986) Van Galen, Smyth, Meulenbroek & Hylkema (in press)
Chapter 2	Meulenbroek & Van Galen (1988)
Chapter 3	Meulenbroek & Van Galen (1986)
Chapter 4	Meulenbroek & Van Galen (submitted) Meulenbroek & Van Galen (1988)
Chapter 5	Meulenbroek & Van Galen (in press)
Chapter 6	Meulenbroek & Van Galen (in press)
Chapter 7	Meulenbroek & Van Galen (1988) Meulenbroek (1989) Hylkema, Meulenbroek & Van Galen (1988)

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Chapter 2

The production of line drawings

FOREPERIOD DURATION AND THE ANALYSIS* OF MOTOR STAGES IN A LINE DRAWING TASK*

Ruud G. J. Meulenbroek and Gerard P. Van Galen

This study examines the effects of foreperiod duration and three motor variables on latencies and movement velocities of a line drawing task. The motor side of the reaction process leading up to precise drawing movements was assumed to entail three stages, which in an earlier study we labelled motor programming, parameterization and initiation. In the present study we investigated the relationship between key variables to these motor stages and foreperiod duration. The results showed that *number of elements*, *movement size*, and *movement direction* had independent contributions to choice reaction times of the line drawing task. This finding is in accordance with our stage model. Foreperiod duration showed a significant interaction with movement size and additive effects with number of elements and movement direction. It may be concluded that the effect of foreperiod duration on the motor stages of choice reaction time may be regarded as a bypassing effect causing non-muscle specific variation of the level of motor activation as proposed by Sanders (1983).

INTRODUCTION

A number of experiments (Sanders 1977; Sanders 1980a; Sternberg et al. 1980; Spijkers & Walter 1985) suggest that the effects of foreperiod duration may have their locus on the motor side of the reaction process. Naätänen and Merisalo (1977) and Sanders (1983) have suggested that these effects consist of fluctuations in the level of motor activation beneath, and with high levels of activation around, the *motor action limit*. Psychophysiological results support a motor activation hypothesis of time uncertainty by showing that (1) the amplitude of the late contingent negative variation (CNV) reflecting motor preparation, (Loveless & Sandford 1974; Rohrbauch, Sydulko & Lindsley 1976) is inversely related to foreperiod duration (Gaillard & Perdok 1980); (2) the effects of amphetamine interact with those of time uncertainty and appear to speed up motor rather than perceptual processing (Frowein 1981). At the motor side of the reaction process Sanders (1980b) has proposed a Motor Programming and a Motor Adjustment stage. A *structural* motor variable, like *response specificity* - i.e., the extent the alternative

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responses have a common vector - would affect motor programming while *functional* variables, such as *instructed muscle tension*, *accessory stimuli* and *foreperiod* would affect a more peripherally located motor adjustment stage. Sanders (1977) has pointed out that the combined effects of functional task variables cause an aspecific preparation of the subject while structural task variables affect the direction of the ongoing activity. The locus of both types of variables can be explored by means of the additive factor method (Sternberg 1969). With this method it is possible to investigate the locus of effect of task variables by investigating their mutual relationships on choice reaction time (CRT).

A further partitioning of motor programming and motor adjustment was proposed by Van Galen and Teulings (1983) and by Van Galen, Meulenbroek and Hylkema (1986). They formulated three stages of processing. The first stage (motor programming) retrieves an abstract motor programme from long term motor memory and loads this programme into a short term motor buffer (Henry & Rogers 1960). In a subsequent parameterization stage the abstract motor programme is adapted for real time execution by the substitution of parameter values for force and time. Finally, in the initiation stage, the programme with its parameter values are *unpacked* (Sternberg et al. 1980) in such a way that the recruitment of an appropriate number of motor units and their locations can take place, dependent upon the actual anatomical and physical context of movement execution. Van Galen and Teulings (1982) presented experimental evidence for three motor stages by demonstrating that in a line-drawing task there were additive effects on CRT of (a) the number of elements of the task, (b) the spatial accuracy demands and (c) the anatomic effects of wrist versus finger movements. Van Galen and Teulings (1983) again found evidence for such a three-stage model of motor preparation in an analogous experiment with a letter writing task in which they varied the structure of the motor pattern, the size of the pattern and the anatomical system of the first element of the movement pattern.

To test Sanders' suggestions that foreperiod duration affects motor adjustment we explore in the present study the relation between the effects of foreperiod duration (150 and 1500 ms) and number of elements, movement size and anatomic effects of wrist versus fingers in a line-drawing task. A secondary aim was to reconfirm the results of the aforementioned studies concerning the relation of these key variables to our stage model. As repeatedly argued by proponents of the additive factor method, the results of a single experiment cannot be trusted, and in particular additive results should be repeatedly observed in order to gain credibility.

Given the further differentiation of *motor adjustment* (Sanders 1980b) into the stages of parameterization and initiation (Van Galen & Teulings 1983) it is not clear whether foreperiod duration has its locus of effect on the parameterization stage, on the initiation stage or on both. However, if parameters for real time execution are set in a global manner, independently of the preparation of specific limbs and muscles which initiate the movement, it follows that aspecific activation of the motor system as a result of time uncertainty should affect the non-muscle specific parameterization stage more likely than the muscle-specific initiation stage. Supportive evidence for this hypothesis can be found in psychophysiological experiments on the effects of warning signals on preparing motor acts (Requin 1980; Brunia 1980; Haagh & Brunia 1984). These studies suggest two components of motoric activation: (a) a general wave of activation spreading to the ipsilateral as well as to the contralateral side of the body, and (b) a more specific activation of the limb involved in the current action. However, the latter studies were performed with simple reaction time tasks where it is possible for the subject to prepare a specific muscle group before the RT interval. In the present study we measured choice reaction times in which only a general activation of the muscular system is appropriate. We therefore assume that variation of foreperiod is related to a variation of the level of generalised activation.

It is known that size variations in writing tasks are foremost realized by *force* rather than by *duration* of the movement (Denier Van Der Gon & Thuring 1965). We therefore investigated movement velocity as a second dependent variable in this experiment because size variations in small line drawings affect movement time less than movement velocity. Van Galen and Teulings (1983) found that size, as a global performance variable in handwriting and drawing, is realised by an increased level of activation in the neuromuscular system as a whole. It may be expected that foreperiod duration and size have a common locus of effect on the reaction process and therefore, according to the additive factor method, will have interactive effects on CRT.

In order to supply further evidence for a separate stage of muscular initiation, independent of parameterization, we varied in addition to the aforementioned variables the anatomical character of the starting movement. In half of the trials the first drawing element was performed by a wrist movement. In the other half of the trials the movement was initiated by either extending or flexing the fingers.

METHOD

Task and apparatus

Subjects were seated at a table. At a position that was comfortable for drawing, a normal sheet of paper covered a XY digitizer (Calcomp 9240) with an RMS error of less than 0.2 mm. The drawing task was performed with the right hand with a normal ballpen which was connected to a PDP 11-45 computer through a flexible wire. To eliminate forearm movements, the forearm was placed and fixed to a cuff that was attached to the digitizer. The cuff could be adjusted to the subjects' forearm diameter (see Maarse et al. 1986). In front of the subject a rapid display screen (Vector General) was placed at a distance of 135 cm from the subjects' position. Subjects visually fixated this screen. The task consisted of copying as fast and accurate as possible with the pen a line drawing which was presented visually on the screen. At the start of a trial subjects held the pen in a starting position on the tablet which corresponded to the centre of the display screen. Then, a visual warning stimulus consisting of an asterisk was presented for 150 ms at the centre of the screen. After a foreperiod duration of either 150 or 1500 ms (constant within a block of trials) a visual imperative stimulus was displayed for 150 ms. In half of the trials the stimulus consisted of *one* line, starting at the centre of the screen and ending at one of the four bisection points of the sides of a virtual diamond (fig.1). In the other half of the trials the stimulus consisted of *two* connected lines of equal length, one starting at the centre of the screen and ending at one of the four bisection points, the other starting at the bisection point and ending at one of the corners of the diamond. The movement size for single as well as double lines was indicated by the length of the displayed lines which was either 1 cm or 2 cm. The position of the subjects' arm and the starting position of the pen on the XY tablet were arranged so that lines in the lower-left to upper-right direction (and vice versa) would be drawn with only movements of the wrist while lines from the lower-right to upper-left direction (and vice versa) would be only drawn with movements of thumb and fingers. After presentation of the imperative signal pen movements were recorded with a sampling frequency of 105 Hz during a period of two seconds. During the sampling period immediate visual feedback of the drawing trace was given. At the end of the sampling period the feedback disappeared from the display, followed by a period of 1400 ms in which the subject replaced the pen at the starting position on the XY tablet. The replacing of the pen was done with the aid of immediate visual feedback of pen movements. A trial ended with a restperiod of two seconds in which only the current penpoint position (the starting position for the next trial) was displayed. Movement latencies (RTs) and mean movement

GRAPHIC DISPLAY OF STIMULI

S = starting position of the penpoint

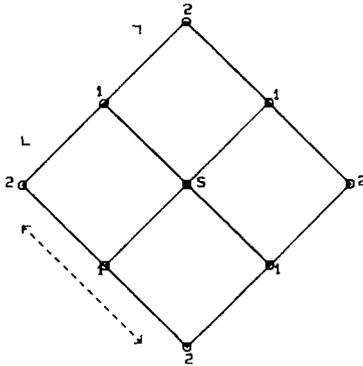
NUMBER OF ELEMENTS

1 = bisection points of the diamond.

(endpoints 1-element task)

2 = cornerpoints of the diamond.

(endpoints of 2-elements task)



SIZE VARIATION

distance S → 1 was either 1 or 2 cm

MOVEMENT DIRECTION (anatomical system)

dotted direction wrist movements

striped direction finger movements

Figure 1. Graphic display of stimuli and experimental conditions. S = centre of display and starting position of penpoint. One line starting at S and ending at one of the four bisection points of the sides of a diamond (1) indicated the movement direction of the first element. When a second line had to be drawn a second line was displayed starting at (1) and ending at one of the two corner-points (2) along the bisected side of the diamond indicating the movement direction of the second element. Required movement size was indicated by the size of the displayed stimulus lines (1 or 2 cm; equal lengths of lines in the 2-element task situation). Movements along the direction indicated by the dots consisted of wrist movements, along the direction indicated by the stripes consisted of finger movements.

velocities were measured by means of an interactive computer analysis within the pattern of absolute velocities of the tip of the pen. Movement latency (RT) was defined as the time in ms between the onset of the stimulus and the start of the movement. Separate strokes were segments lying between successive points of zero velocity.

Subjects

Fourteen paid righthanded writing students served as subjects. Each subject was trained on the line-drawing task until a stable reaction time level was reached with a standard deviation of no more than 10% of the mean reaction

time. The training consisted of a series of trials with short and a series of trials with long foreperiod durations. In both series all movement patterns were trained equally often. Training series with short and long foreperiod durations were counterbalanced across subjects. Subjects were instructed to draw as fast and as accurate as possible the stimulus drawings presented as reaction signal. We tried to avoid confounding of accuracy and task variable effects by having no special tolerance limits with regard to movement size and movement direction during practice and experimental trials.

Procedure

The experiment consisted of two blocks of trials, each block containing three warm-up and 192 experimental trials. At random places within blocks nineteen catch trials (a plus sign on the display indicating that no movement was required) were interspersed. In one block the foreperiod between the visual warning and imperative signals amounted to 150 ms, which was 1500 ms in the other block. The two blocks were counterbalanced over subjects. Each block of trials had a different random order of experimental trials. Stimulus uncertainty varied on three dimensions: number of lines (one versus two lines), line size (1 versus 2 cm), and movement direction (wrist versus finger movements). Care was taken to counterbalance abduction and adduction of the wrist and flexion and extension of thumb and fingers in the one-element as well as in the two-element movements (see fig.1). Data analyses consisted of analyses of variance. Cell entries for the analysis of latencies and movement velocities of the first element were the medians of 24 replications of each condition per subject (2 foreperiods * 2 number of lines * 2 line sizes * 2 movement directions * 24 replications making up 2 blocks of 192 trials). Similarly the movement velocities of the second element in the two-element movements were also analyzed by entering the medians of 24 replications into an analysis of variance (2 foreperiods * 2 line sizes * 2 movement directions * 24 replications making up 192 trials containing two elements).

RESULTS

Errors and spatial accuracy

Errors were rare in this highly compatible line-drawing task. With short foreperiod durations 0.56% decision errors (i.e., wrong number of elements and/or wrong movement direction) occurred whereas this percentage amounted to 0.26 % with long foreperiod durations. No anticipation errors (RT < 100 ms) were observed.

Small and large stimulus drawings resulted in significant but small

variations in movement distance of the first as well as of the second element. The mean movement distance of the first element was 1.305 cm in the small, and 1.686 cm in the large size condition ($F(1,13)=388.52$; $p<.01$). Mean movement distance of the second element was 1.319 cm in the small, and 1.583 cm in the large size condition ($F(1,13)=86.99$; $p<.01$). Movement distance varied little as a result of size instructions because (1) lines of 1 and 2 cm were presented on a screen 135 cm in front of the subject and (2) no spatial tolerance limits for the subjects' performance were used. Size effects on movement distance were equal across experimental conditions except for a significant reduction in movement distance of the first element (0.074 cm) when this element was performed in the context of a second element ($F(1,13)=16.98$; $p<.01$).

Table 1
Results of analysis of variance on the CRT data.

Effects	F(1,13)	p
1. Number of elements	112.20	<.01
2. Movement size	5.37	<.05
3. Movement direction	21.30	<.01
4. Foreperiod	34.95	<.01
Interactions		
1 x 2	0.92	>.10
1 x 3	.18	>.05
2 x 3	.48	>.10
1 x 4	.16	>.10
2 x 4	.56	<.03
3 x 4	.44	>.10

CRT data

Table 1 summarizes the main effects and interactions of the CRT data. Number of elements had a significant ($F(1,13)=112.2$; $p<.01$) effect on CRT: on the average the 1-element task situation was 37 ms faster than the 2-elements task situation. Movement size had a small, but also significant ($F(1,13)=5.37$; $p<.05$) effect on CRT: the large figures were 5 ms faster than the small figures. The effect of movement direction was also significant ($F(1,13)=21.30$; $p<.01$): lines initiated by wrist movements had 7 ms shorter CRTs than lines initiated by finger movements. The latter two main effects seem to be rather small in relation to the temporal resolution with which the

drawing movements were sampled (i.e., 105 Hz) and therefore have to be interpreted with care but the number of replications per cell ($N=24$) as well as the spatial resolution of the digitizer (less than 0.2 mm) gave no reason to treat the effects as artifacts of the measurement procedure. The pattern of interactions shows that the effects of number of elements, movement size and direction were additive although the interaction between number of elements and direction fell just below the .05 significance level ($F(1,13)=4.18$; $p=.0593$). Fig.2 depicts these effects on CRT of number of elements * movement size (upper-left graph), of movement size * movement direction (upper-middle graph) and of number of elements * movement direction (upper-right graph).

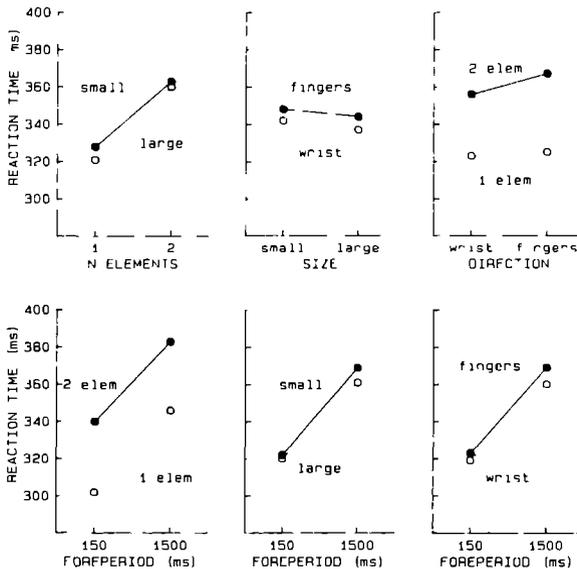


Figure 2. Averages of the median latencies for the line drawing task as a function of: number of elements and movement size (upper-left graph), movement size and movement direction (upper-middle graph), movement direction and number of elements (upper-right graph), foreperiod duration and number of elements (lower-left graph), foreperiod duration and movement size (lower-middle graph), foreperiod duration and movement direction (lower-right graph).

Foreperiod duration had a significant effect on CRT ($F(1,13)=34.95$; $p<.01$): mean CRT with a foreperiod duration of 150 ms was 321 ms; at 1500 ms this amounted to 365 ms. The lower part of Figure 2 shows the effects of

foreperiod duration and, number of elements (lower-left graph), movement size (lower-middle graph) and movement direction (lower-right graph). The analysis of variance showed no significant first order interaction of foreperiod duration with number of elements ($F(1,13)=0.16$; $p>.10$). Foreperiod duration and movement size significantly interacted ($F(1,13)=6.56$; $p<.03$), whereas the interaction between foreperiod duration and movement direction appeared not to be significant ($F(1,13)=1.44$; $p>.10$). While the main effects on CRT of movement size and direction were very small (5 and 7 ms, respectively) it appeared that the effect of movement size was so consistent that its interaction with foreperiod duration reached significance whereas the interaction between direction and foreperiod duration did not. No significant higher-order interactions were present.

Table 2
Results of analysis of variance on velocity data.

Effects	First element		Second element	
	F(1,13)	p	F(1,13)	p
1. Number of elements	6.00	<.03		
2. Movement size	159.49	<.01	133.39	<.01
3. Movement direction	83.56	<.01	38.12	<.01
4. Foreperiod	1.85	>.10	0.84	>.10
Interactions				
1x2	1.46	>.10		
1x3	14.47	<.01		
2x3	16.15	<.01	12.02	<.01
1x4	0.03	>.10		
2x4	0.09	>.10	0.03	>.10
3x4	0.03	>.10	0.37	>.10

Velocity data

Table 2 summarizes the main effects and interactions of the velocity data of the first and second element. The mean velocity of the first element (V1) was larger in the one-element than in the two-element task (V1: 6.767 and 6.519 cm/s respectively; $F(1,13)=6.0$; $p<.03$). Small line drawings were significantly slower than large line drawings (V1: 5.998 and 7.294 cm/s respectively; $F(1,13)=159.49$; $p<.01$; V2: 6.740 and 7.516 cm/s respectively; $F(1,13)=133.39$; $p<.01$). Wrist movements performed as first element of the line-drawing task were significantly faster than movements of thumb and fingers as first element (V1: 7.210 and 6.071 cm/s, respectively; $F(1,13)=83.65$; $p<.01$). As second element, however, wrist movements were performed significantly slower than finger movements (V2: 6.167 and 8.100

cm/s respectively; $F(1,13)=38.12$; $p<.01$). This last effect may account for the interaction of number of elements and wrist/finger movements

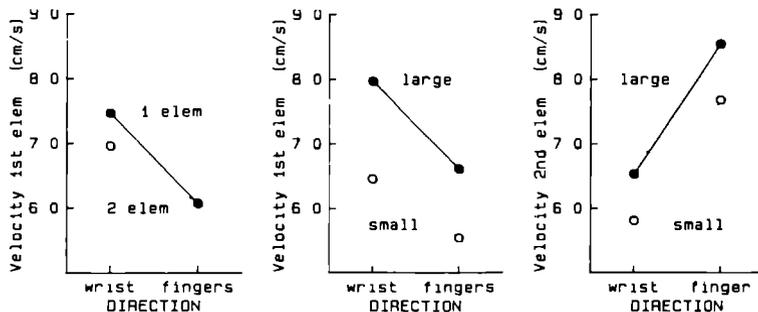


Figure 3. Mean drawing velocity: of first element as a function of movement direction and number of elements (left graph), of first (middle graph) and second element (right graph) as a function of movement direction and movement size.

($F(1,13)=14.47$; $p<.01$) which was observed in the V1-data (fig.3; left graph). Two other interactions, between movement size and direction were observed in the velocity data of the first and second element. In the first element movement size had a larger effect on the velocity of wrist movements than on the drawing velocity of finger movements ($F(1,13)=16.15$; $p<.01$ - fig.3; middle graph). In the second element, however, movement size affected the drawing velocity of finger movements stronger than the drawing velocity of wrist movements ($F(1,13)=16.15$; $p<.01$ - fig.3; right graph). Foreperiod duration did neither have a main effect upon velocity, nor any interaction with the other variables.

DISCUSSION

CRT data

Our results show additive contributions of number of elements, movement size and movement direction to choice reaction times in a line-drawing task. Although these effects still need further verification because the interaction between number of elements and movement direction only fell just below the .05 level of significance, this outcome is consistent with the linear stage description of the motor aspects of drawing and writing as proposed by Van Galen and Teulings (1982; 1983). They found similar evidence suggesting three independent motor processing stages : (a) motor programming, i.e., the retrieval of an abstract motor programme; (b) parameterization, i.e., the

substitution of parameters for force and time in the abstract programme; and (c) movement initiation, i.e., the recruitment of the required motor units of the anatomical apparatus. The distinction between motor programming and parameterization in the present model needs some further discussion. Motor programming is often conceptualized as the successive specification of movement parameter values of an abstract, non-motor representation into a format appropriate for force production (e.g. Kerr 1978; Rosenbaum 1980; Keele 1981; Kelso 1981; Klapp 1977; Schmidt 1982; Spijkers 1987). According to our view, motor programming is often referred to when the specification of kinematic movement parameters is investigated. Experiments concerning the preprogramming of movement parameters (Rosenbaum 1980; Zelaznik, Shapiro & Carter 1982), i.e., the specification of parameter values prior to the reaction signal, may have contributed to referring to programming aspects rather than to parameterization aspects of movement control. On the contrary in the study of complex motor behaviour like speech, handwriting and gesture (Van Galen & Wing 1984) the term programming has got the meaning of an abstract, i.e., non-muscle specific, description of the movement pattern. For drawing (Van Galen 1980) and handwriting (Van Galen & Teulings 1983) it was argued that this abstract representation needs further parameters for size and speed, and a muscular realisation appropriate for the current anatomical and biophysical context. It appears that *motor programming* is an ambiguous term and its conceptualization depends upon the experimental design and variables under investigation. However, it should be stressed that the essential question is not the name of a stage but the probable number of independent stages responsible for the variation of reaction time as indicated by repeatedly found additive effects. The additive effects of number of elements and size found in this experiment as well as the additive effect of the structure of a movement pattern and spatial accuracy demands (Van Galen & Teulings 1983) indicate that the activation of the general structure of a movement and the specification of kinematic movement parameters are independent stages. In addition one might argue that motor programming as defined in the present model refers to the stage of response selection in which an abstract response code is activated as a result of stimulus-response alternatives or instructions which vary the compatibility of the relation between stimulus and response. The validity of the distinction between the motor programming stage defined as the retrieval of an abstract motor programme from long term motor memory after a response code is activated in the response-selection stage, and the parameterization stage, in which the specification of kinematic movement parameters takes place, needs further verification in experiments in which the combined effects of a wider range of response selection and

motoric task variables (e.g., S-R compatibility, number of elements, element sequence, element size, spatial accuracy and movement direction) are investigated.

We found additive effects of foreperiod duration and number of elements which is consistent with Sanders' proposition that motor programming is not influenced by general preparation processes. The finding that foreperiod duration interacted with that of movement size but not with movement direction suggests that time uncertainty has its locus of effect on parameterization rather than on movement initiation. As mentioned in the introduction small size variations in drawing and writing tasks are foremost realized by force rather than by duration of the movement (Denier van der Gon & Thuring 1965). Rosenbaum (1980) has shown that the preparation of movement size is even possible if the muscles with which the movement is performed are not yet known. Because time uncertainty is supposed to influence the overall level of motoric activation (Naätänen & Merisalo 1977; Sanders 1983) interactions between effects of time uncertainty and movement size can be readily expected. Spijkers and Steyvers (1984) and Spijkers and Walter (1985) found additive effects of foreperiod duration and instructed movement velocity in reaction time experiments of discrete sliding movements of the arm. These results seem not to correspond with the interaction between foreperiod duration and movement size found in the present experiment. Spijkers and Steyvers (1984) showed furthermore that the effects of instructed velocity on reaction time disappeared when the required velocity was precued in advance of the reaction signal. In their experiments *velocity* was manipulated by having the subjects produce accurately equidistant sliding movements of varying durations whereas in our experiment non-equidistant movements were required without specific spatial tolerance limits. The manipulation of required movement duration instead of movement distance might have led to the presetting of different movement strategies for the short- and long-duration movements and not to the actual setting of the force/speed parameter dependent upon the information in the reaction signal. In this way additive effects between the variable instructed velocity and the variable foreperiod duration might have been expected since the former variable relates indeed more to motor programming than to parameterization. Semjen, Requin and Fiori (1978) reported additive effects between foreperiod duration and movement extent in a pointing task. However, this effect fell just short below the .05 significance level ($F(6,42)=2.27$). Foreperiod duration contained four levels, 1, 2, 3 and 4 s in their experiment and the interaction between foreperiod duration and movement distance appeared to be significant in a separate

analysis with foreperiod durations of 1 and 2 sec only ($F(2,14)=4.34$; $p<.05$). A significant linear component of the interaction between foreperiod and target distance was also found in subsequent trend analyses. Their results indicated that reaction time differences between short and long movement distances increased as the duration of the foreperiod increased. These results correspond to the interaction between foreperiod duration and movement distance found in the present experiment. Semjen et al. (1978) also reported a significant interaction between movement direction and foreperiod duration but since a pointing task was used it might be argued that in reaching to a specific target accuracy demands are confounded with aspects of movement direction and, as Van Galen and Teulings (1983) have shown, accuracy demands are referred to in our model as aspects of the parameterization stage.

Further the results showed that lines of 1 cm resulted in longer reaction times than lines of 2 cm. This may be explained by assuming that the preparation of antagonist activity to stop the pen has to occur within the RT interval in the case of 1 cm figures whereas this might be delayed in the case of 2 cm figures. The preparation of shorter lines seemed therefore more demanding than the preparation of longer lines. This could explain the direction of the interaction between foreperiod and size on CRT. In the case of the longer foreperiod duration the simultaneous preparation of the start and stop of a 1 cm line resulted in larger reaction times than with short foreperiod durations because general motor activation drops to a lower level with longer foreperiod durations. This process seems to occur independently from the muscles with which the movement is performed.

Velocity data

Overall the velocity data confirmed the CRT effects. Drawing two lines did not only increase reaction time but also slowed down the velocity of drawing the first element. This finding is consistent with the view that motor programming is a process which partly continues during the execution of a task. It seems that during the longer RT for two-element figures programming is only partially performed. One might argue that ongoing programming activities during the execution of the task is in conflict with additive factor methodology. This argument would apply, however, if the degree of programming during the RT-phase would be left to strategic choices of the subject. In that case one would not expect reliable effects upon RT. With regard to the one versus two-element figures in our experiment we found a consistent effect of longer RTs for two-element figures. At the same time, however, it appeared that the *unpacking* (Sternberg et al. 1978; 1980)

of the final details of the second element of the drawing task seemed to occur concurrently with the real-time performance of the first element. Comparable *unpacking* effects have been found in earlier experiments with drawing and writing tasks (Van Galen & Teulings 1982, 1983; Van Galen et al. 1986).

Movement size significantly influenced drawing velocities. The finding of faster movements along longer trajectories is compatible with the finding of increased velocities until a maximum speed is accomplished in longer strokes in handwriting tasks (Denier Van Der Gon & Thuring 1965). We already assumed that in the case of the 1 cm figures antagonist activity to stop the pen has to be activated before the agonist reaches its maximum velocity. The latter finding is compatible with the outcome that the RT-data show *longer* RTs for the small figures. The interaction between number of elements and movement direction on drawing velocity showed that the proximal, single-joint, wrist movements are easier to perform as a first element followed by more distal, multi-joint, finger movements than as a second element preceded by such finger movements (Van Sommers 1984).

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Chapter 3

The production of stroke sequences

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

Ruud G. J. Meulenbroek and Gerard P. Van Galen

In this study we investigated movement dynamics and frequency spectra of up and downstrokes of repetitive writing behaviour of first, second and third grade primary school children. The subjects performed preparatory cursive writing patterns (loops, arcades, wave forms and zig-zags) varying in length and size under different speed-accuracy and lineation conditions. The experiment provides empirical data on the effects of the task variables *length*, *degree of continuity* and *direction of rotation* of writing patterns on writing performance measures and the quality of stroke production. We describe changes in the writing behaviour of young children as a result of increasing age and as a result of different size, speed-accuracy and lineation instructions.

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

* *Graphonomics: Contemporary research in handwriting* (1986), H.S.R. Kao, G.P. Van Galen and R. Hoosain (Eds.), Amsterdam: North Holland (pp. 71-92).

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-yr.-old children and controlled by a guidance system in 7-yr.-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, Viviani, Hauert and Guyon (1985) on manual tracking skills of 5- to 9-yr.-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 1986). 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 et al. 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 1986), 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 lineation 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 analyzing 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 1986). 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 practising the 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 linguistic and

psychomotoric processes take place in a parallel manner (Van Galen & Van der Plaats 1984). 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 1986). 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 continuous 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 clock- and 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 repetitive 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 1986). 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 lineation 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 righthanded 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 schoolchair and in front of a schooldesk 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 lineation, which was fixed to the XY-tablet. The XY-tablet was rotated 15 degrees anticlockwise 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

Task 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).

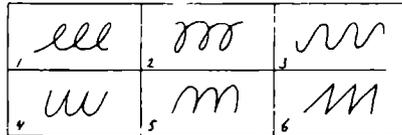


Figure 1. Copying patterns used in the experiment. Pattern numbers correspond to the text.

The paper on which the subjects wrote in task 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 lineation instructions

For task C the patterns 1 and 2 (Fig. 1) were used with different sizes, speed-accuracy and lineation 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. *Lineation 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 lineation 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 lineation conditions.

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 & Jones 1986) 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 & 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).

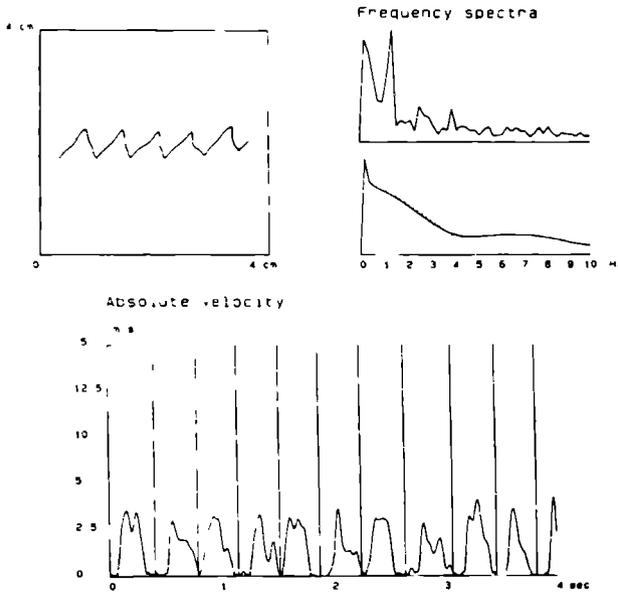


Figure 2. Example of data analysis of a copying sample (upper-left-panel) with corresponding absolute velocity pattern (lower-panel; vertical lines represent strokeboarders) and optimal scaled amplitude frequency spectra (upper-right-panel): the upper graph represents the spectrum of the whole sample,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

RESULTS

Task 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 task A and B (see Fig 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 repetitive writing behaviour. Children, apparently profiting from rehearsal, performed long patterns with faster movement characteristics than short patterns, whereas the reverse was 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 (Fig.5; lower panels) it can be observed that the distribution of energy along the spectrum is different for up

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	mov. time (s)	mov. dist. (cm)	mean vel. (cm/s)	max. vel. (cm/s)	sd	sd	sd	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	0.945	.197	1.314	.373	2.456	.645
c	.213	.054	.825	.154	4.404	.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	0.899	.240	1.521	.574	3.062	1.026
c	.255	.031	0.992	.139	3.330	.554	7.940	1.060

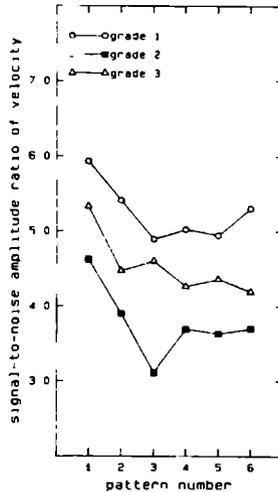


Figure 3. Signal-to-noise amplitude ratios of the copying performance of six patterns used in task A and B for separate grades. Pattern numbers correspond to the text.

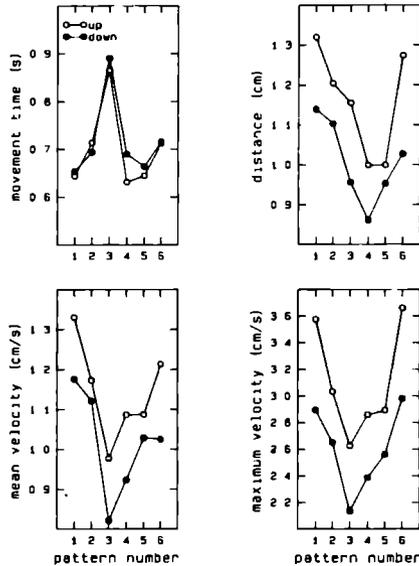


Figure 4. Movement time (upper-left panel), movement distance (upper-right panel), mean velocity (lower left panel) and maximum velocity (lower-right panel) of upstrokes (open circles) and downstrokes (closed circles) of the copying performance of the six patterns in task A and B.

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 Fig.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.

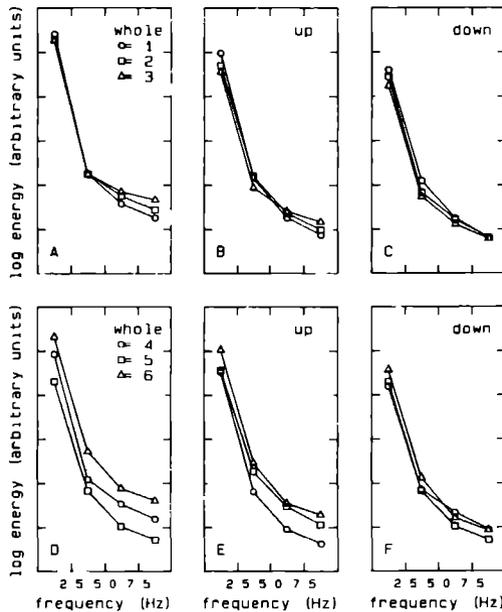


Figure 5. Energy distributions in four equal frequency bands of the copying performance of continuous patterns (upper panels) and discontinuous patterns (lower panels) calculated from the absolute velocity data of the whole pattern (left panels), upstrokes (middle panels) and downstroke (right panels).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

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 Fig. 4). The means of the anti-clockwise patterns (1 & 4) and the clockwise patterns (2 & 5) did not differ significantly (means: .654 s/stroke and .678 s/stroke respectively). The results partly confirmed our hypothesis concerning the effects of direction of rotation on performance measures of repetitive 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 (Fig.5; upper panel) changes from anti-clockwise (Fig.5A circles) to clockwise (Fig.5A squares) to an alternation of these two (Fig.5A triangles) the amount of energy of high movement frequencies increased and of low movement frequencies decreased (Fig.5A; $F(3,78)=4.98$; $p<0.001$). This interaction occurred predominantly in the upstrokes (Fig.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 Fig. 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 ($F(9,29)=2.3$; $p<0.05$). 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 lineation 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 corresponding 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 lineation instructions.

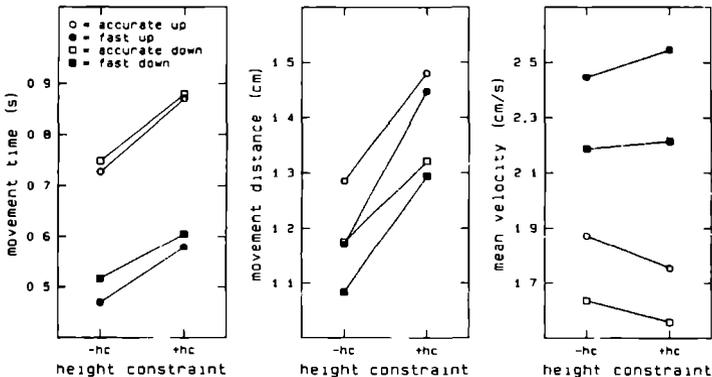


Figure 6. Movement time (left panel), movement distance (middle panel) and mean velocity (right panel) of upstrokes (circles) and downstrokes (squares) in the absence or presence of a height constraint (X-axis) and under accuracy- (open markers) and speed-instructions (closed markers).

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 constraint 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 task 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 observed as a result of speed instructions (Fig.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).

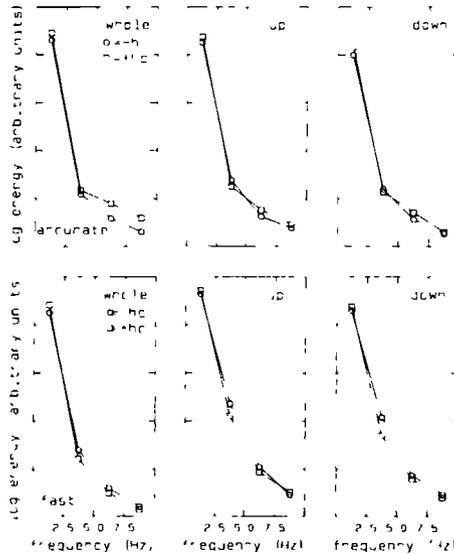


Figure 7. Energy distributions in four equal frequency bands of the copying performance in task C under accuracy instructions (upper panels) or speed instructions (lower panels) and under the absence (circles) or presence (squares) of a height constraint calculated from the absolute velocity data of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

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, 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. However, the analysis of the spectrum of the velocity data showed that continuous transitions ask for more coordination and entail more movement instability: trajectories connecting upstrokes with downstrokes along an *arcadic*, i.e., continuous, curve (Fig 1, pattern 5) had more energy in the high frequency band than comparable trajectories that end in sharp transition points (Fig 1, pattern 4). 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 automated process at the age levels of our subjects and place an extra demand upon writing performance.

The direction of rotation of continuous repetitive 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 repetitive 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, 1982).

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 (1979; 1981) 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 plotted 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 (Fig. 8; right panel) are nicely in agreement with the hypothesis that the number of phase

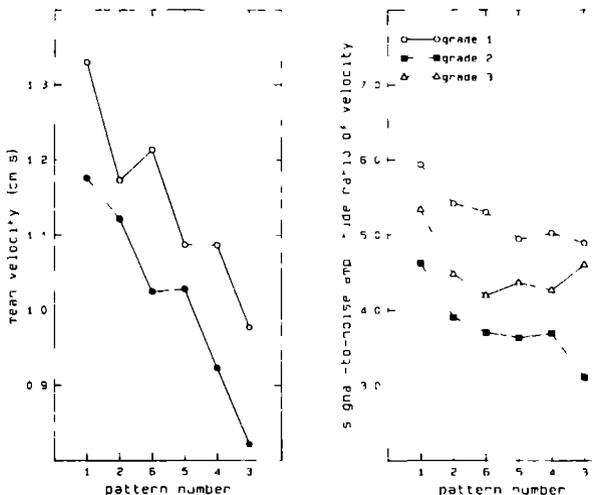


Figure 8. Rearrangement of pattern order for the mean velocity data (left panel) and signal-to-noise amplitude ratios (right panel) of task A and B according to increasing pattern-complexity defined by increasing number of phase transition points per pattern.

transition points per trajectory defines the motoric complexity of a 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 repetitive writing patterns stroke by stroke. The childrens' performance measures of up- and downstrokes were equally effected by the presence of an upperline whereas with the adult control subjects downstrokes 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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Chapter 4

The production of letter forms

PERCEPTUAL MOTOR COMPLEXITY OF PRINTED AND CURSIVE LETTERS*

Ruud G.J. Meulenbroek and Gerard P. van Galen

In this paper a number of factors determining the perceptual motor complexity of letter forms are discussed. An experiment is reported in which primary school children wrote twice the lower-case letters of a cursive alphabet, once after the visual presentation of printed and once after the visual presentation of cursive stimulus letters. Response-initiation-time differences between these two types of experimental trials were considered to reflect a cognitive translation process from the graphemic to the motoric level. The analyses revealed that spatial ambiguity, allographic variability, contextual ambiguity and letter frequency are determinants of the time needed by children for perceiving printed and producing corresponding cursive letters. The motoric complexity of writing cursive letters was investigated by analyzing writing velocity, dysfluency and curvature measurements of produced grapheme segments. The analyses indicated that letter frequency and the curvature of grapheme segments determine the motoric complexity of cursive graphemes. Educational implications based on these findings are discussed.

INTRODUCTION

Printed versus cursive letter presentation

Learning to write involves the mastering of printed and/or cursive letters, a complex learning process with both cognitive and motoric aspects. Models of reading and writing, like those of Ellis (1982) and Margolin (1984), state that in order to write (or read) correctly, a subject must have sufficient lexical knowledge (lexical route) or have a set of phoneme-grapheme translation rules with which phonological codes can be translated into graphemic codes (phonological route). In both ways a motor program is activated and stored in a short term motor buffer. The motor program controls the motoric output process and consists of an abstract code (Keele 1981) representing the number of strokes and their spatial relations (Van Galen & Teulings 1983). When a graphemic code is activated the output process is still under the influence of allographic variability (Wing, Nimmo-Smith & Eldridge 1983; Van Galen & Van der Plaats 1984). Allographs are different motoric

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realisations of one letter or grapheme, e.g. the *r* and *R* are two allographs of the grapheme *r*. Besides having to learn the printed letter forms in order to read, children have to learn the allographic variations of the letters of the written language in order to build up a sufficient number of motor programs with which handwriting can be acquired.

Before learning to produce cursive graphemes a child has already been familiarized with printed letters and is able to read short words (Barbe, Lucas & Wasylyk 1984). When children learn to read they are often allowed or instructed to copy printed letters in order to improve letter recognition. In elementary writing education children also often start by drawing printed letters (Barbe et al. 1984). A considerable amount of research has been concentrated on the advantages and disadvantages of *manuscript writing*, i.e., the writing of printed letters, and the problems which may occur when children have to realize a transition from *manuscript to cursive handwriting* (Barbe et al. 1984). In many countries the first few years of writing education are concerned with writing printed letters. Cursive letter forms are introduced somewhere between the second and fourth grade (Barbe et al. 1984). In The Netherlands first grade pupils have no more than five months practice in writing printed letters before they start to learn cursive handwriting. Recently Dutch reading and writing exercises have been combined into one curriculum in which printed letters are restricted to reading and cursive letters to writing exercises. In the latter case letter forms, printed as well as cursive, are introduced simultaneously but only the cursive ones have to be written (see fig. 1). From a theoretical point of view this educational situation presents a child with a rather complex learning situation. Reading asks, according to our analysis, the command of a many-to-one strategy of information processing: The child must learn that both printed and cursive forms of letters should evoke one single phoneme. In the writing situation, however, the task is of a one-to-many mapping type. Depending upon the task (printed versus cursive writing) the child has to select his motor programs from quite divergent repertoires. It is the latter stimulus-response ambiguity which is studied in the present experiment. The present study concentrates upon the effects of the variation of letter type (printed versus cursive) upon the initiation of cursive script.

We therefore designed an experiment in which primary school children had to write lower-case cursive letters under speed instructions. The experiment consisted of two different conditions. In one condition the visually presented letters were printed and in the other cursive. We predicted that the two different conditions would mainly affect response-initiation time and not the

a	b	c	d	e	f	g	h	i	j	k	l	m
a	b	c	d	e	f	g	h	i	j	k	l	m
n	o	p	q	r	s	t	u	v	w	x	ij	z
n	o	p	q	r	s	t	u	v	w	x	y	z

Figure 1 An example of a printed (row 1 and 3) and cursive alphabet (row 2 and 4) as used in a Dutch reading and writing curriculum

kinematics of the cursive writing movements because once the writing movements have started a motor program has already been installed in the short-term motor buffer (Klapp 1979; Van Galen & Teulings 1983). Because of the higher stimulus-response compatibility in the cursive condition shorter response-initiation times were expected in this condition than in the printed letter condition. Because Dutch school children are not used to writing printed letters we did not investigate the effects of the reverse of the aforementioned experimental conditions. Subjects did not have to write printed letters after the visual presentation of different letter forms.

The perceptual or cognitive complexity of printed letters

We hypothesized that the difference in response-initiation times between the printed and cursive letter condition reflects a cognitive translation process from the graphemic to the motoric level in the output process. An inspection of the duration of this process for separate letters of the alphabet might reveal a number of letter-complexity factors of importance to educational practice. Recent investigations with adult subjects have shown that graphemic codes in motor memory contain spatial information and that each allograph is represented by a different motor program in long term motor memory (Van Galen & Teulings 1983, Teulings, Thomassen & Van Galen 1986).

In view of these findings we hypothesized the existence of at least three different aspects determining the difficulty of response initiation of lower-case letters: (1) Spatial ambiguity This factor concerns the widely investigated educational problem of letter reversals (Chapman & Wedell

1972; Sharfman 1973). Letters which are spatially ambiguous, i.e., which change into other letters after rotation (e.g., *b, d, p, q*) present a heavier load upon the motoric initiation process than letters of which the identity stays unaffected by such spatial transformations (e.g., *a, g, k, s*). (2) Allographic variability: letters having many lower-case allographs (e.g., *r, s, t*) are more complex than letters having only one lower-case allograph (e.g., *e, j, o*) because in the first instance the correct allograph has to be chosen from a number of alternatives whereas in the second instance there are no other allographs to choose from. (3) Contextual ambiguity: A third aspect of letter complexity which is important to elementary writing education is the contextual ambiguity of letters. Usually letters are not perceived in isolation. They are preceded and followed by other letters. When a letter has no context, as in many instances of elementary writing education, the form of the letter should be so distinctive that it cannot be mistaken for other graphemes. Letters which are dependent on contextual information for their recognition are for example the printed letters **l, i, o, b, g** and **q** which might respectively be perceived as the digits 1, 1, 0, 6, 9 and 9 as well as the printed letter **x** which might be interpreted as a multiplication sign. Letters which might be regarded as contextually unambiguous are *a, e, f, h, k, s* and *z*.

A factor which might also influence response-initiation time in our task is the frequency with which letters are used in the written language. Van Galen (1980) has shown that in a reaction-time task frequently used graphemes are more easily retrieved from memory than infrequently used graphemes. The latter frequency aspect was defined by the number of times the letter was used within the experiment. By measuring the correlation between response-initiation times and letter frequencies in general we investigated whether the frequency with which letters are used in written language has any relation with the ability of children to recognize letters and retrieve the correct motor programs from memory.

The motoric complexity of cursive letters

In a study of repetitive writing behaviour of primary-school children (Meulenbroek & Van Galen 1986) we found that the motoric complexity of a cursive writing pattern (loop, arcade, wave form and zig-zag) could be defined by the number of points within the pattern at which a new phase-relation had to be set between the two orthogonal muscle-sets which, superimposed on a left-to-right background movement, are often held responsible for the motoric realization of cursive graphemes (Hollerbach 1981). We also observed that the speed and quality of wrist movements in the upstrokes of a zig-zag was higher than of finger movements which are responsible for the downstrokes of this pattern. The most difficult cursive

writing pattern for primary-school children appeared to be the wave-form. We argued that the wave-form pattern called for uninterrupted monitoring of the continuously changing contributions of wrist and finger activity. Because of these results and considering the general maturational direction of motor development from proximal to distal (Gesell 1940) we hypothesized that in learning cursive handwriting the motoric complexity of a cursive grapheme is determined by the amount of accurate finger movements which is needed to realize the grapheme. Thomassen and Teulings (1985) advised developers of writing curricula to refrain from using cursive letter forms with unnecessary high curvatures or sudden curvature changes because these aspects are motorically very demanding and time-consuming. In our experiment we investigated the motoric complexity of cursive letters by measuring the writing velocity in which they were written by normal school children and determining the relation between these measurements and the realized writing dysfluency and maximum curvature data. We hypothesized that motorically complex letters would be written more slowly than less complex letters and that sudden curvature interruptions within grapheme segments would reflect a demand on distal finger activity.

METHOD

Subjects

Seventy-five normal children from an ordinary, urban, primary school served as subjects in the experiment. From the grades two to six we selected 15 children per grade. The mean age of the subjects in years and months was 10;0 with a range of 7;4 to 12;9.

Procedure and apparatus

All subjects performed the experiment in an airconditioned, moderately lit, sound-proofed van. Each subject was seated on a school chair in front of a school desk both adjusted to the body size of the subject. The visual stimuli consisted of two series of 26 slides. A slide-projector projected the stimulus via a special mirror upon the writing surface of the desk. The projection contained no double reflections. On each slide the contours of two adjacent, horizontally placed bright squares and one bright letter of a cursive or a printed alphabet was depicted. Printed and cursive stimulus letters were familiar to the subjects because they were respectively chosen from the reading and writing curriculum of the school. The mirror above the schooldesk was placed in such a manner that the projected body of the smallest letters was 5 mm on the writing surface and the area within the projected contours of the squares had a surface of 30 * 30 millimeters. The

letter was always presented in the centre of the left-hand square. The subject had to write the corresponding cursive grapheme in the centre of the right-hand square.

All subjects were instructed to write the correct cursive grapheme as fast as possible whenever a new letter was presented in the left-hand square. An Apple-2 microcomputer controlled the slide projection and the recording of the writing movements. The latter were sampled at a rate of 100 Hz by means of an Apple-2 XY tablet and a slightly thicker than normal ballpen which were both attached to the micro-computer. After the subject had completed a grapheme the experimenter stopped the sampling period, which had a maximum duration of six seconds, and a high tone was presented as an indication for the subject to shift the non-ruled writing-paper (format A4) upwards to such a degree that the just written letter came to be situated above the two squares. An intertrial restperiod of about twenty seconds was used to store the latency and the sampled writing movements on a diskette.

Printed and cursive stimulus letters were presented blockwise to all subjects and in a random order between subjects. Within the printed and cursive letter condition the letters of the alphabet were randomised for each subject. Each subject performed 52 trials and wrote, in a cursive manner, each letter of the alphabet twice once after the presentation of a printed and once after the presentation of a cursive stimulus letter.

Data analysis

Data analyses were performed by means of a VAX-11/750 computer after filtering the recordings with a low-pass filter of 12 Hz. On visual inspection trials were scored as incorrect whenever the wrong cursive letter was produced or when the letter was incomplete according to the writing curriculum. Of each correct trial the response-initiation time was determined, i.e., the time between the beginning of the presentation of a slide until the beginning of the first stroke of the produced grapheme. Each grapheme was then divided into a prefixed number of upgoing, downgoing and/or horizontal segments by means of an interactive computer analysis system. This standard segmentation of the produced graphemes is depicted in fig. 2. A distinction was made between the initial and final strokes of a grapheme and the body of the letter itself (see fig. 2). Because it was reasoned that in normal handwriting the movement dynamics of initial and final strokes are influenced by preceding and following letters, these strokes were excluded from the analyses.

Of each of the central grapheme segments depicted in fig. 2 the following measures were calculated : movement time, distance, mean velocity, maximum curvature and the number of absolute-velocity

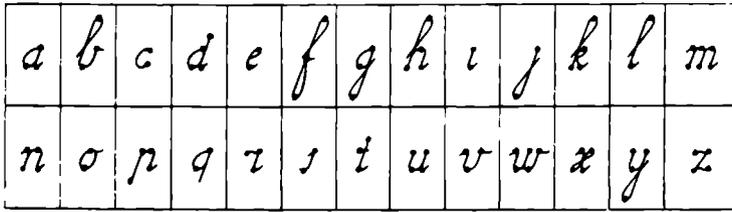


Figure 2. Segmentation of cursive graphemes in data analysis. Dots within the corpora indicate segment-boarders. Initial and final segments of the graphemes were excluded from the data analyses.

disturbances per unit length. An example of the analysis of one trial is depicted in fig. 3. The number of absolute-velocity disturbances per unit length (with exclusion of the velocity dips at the borders of the cut segments) was regarded to reflect the dysfluency with which grapheme segments were produced. It was reasoned that when during the production of a grapheme segment disturbances occur in the absolute-velocity pattern, motoric impulses interrupt the ballistic manner in which a handwriting stroke is

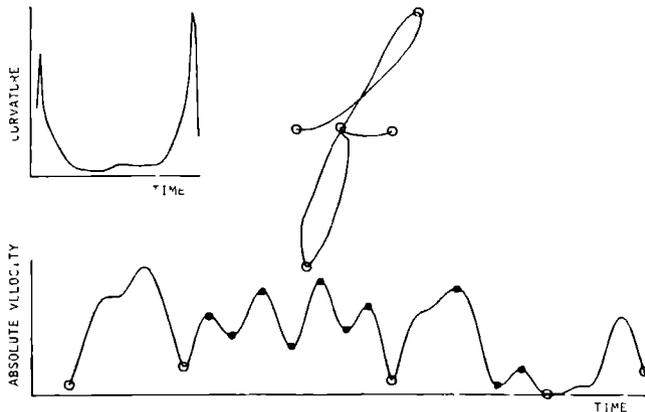


Figure 3. Overview of analysis of one trial. The grapheme *f* (cut in four segments; open circles) and the corresponding absolute velocity pattern of the writing movements (lower graph). Response initiation time (rit), movement time (mt), distance (dist), mean velocity (vel) and dysfluency (vdis, i.e., number of velocity disturbances - closed circles- per unit of length) were calculated on the basis of the absolute velocity pattern. Maximum curvature (curmax) of the central downstroke of the grapheme *f* was calculated on the basis of the upper left graph (see data analysis).

normally produced (Meulenbroek & Van Galen 1986; 1988).

RESULTS AND DISCUSSION

Effects of printed versus cursive letter presentation

Response-initiation-time effects of letter presentation mode

The mean response initiation time in the printed letter condition was significantly higher than in the cursive letter condition (1.22 s and 0.93 s respectively; $F(1,74)=86.48$; $p<.001$). This result corresponded with our hypothesis that in the printed letter condition children need more time to choose the correct motor program than in the cursive letter condition. No significant differences were found between these two conditions with respect to the mean movement time and mean number of absolute-velocity disturbances per produced graheme. This means that the type of stimulus letter did not influence the time needed to perform the cursive letter nor the fluency with which it was written. Small but significant differences were found between the printed and cursive letter condition in the writing distance (2.035 cm and 2.121 cm respectively; $F(1,74)=14.95$; $p<.001$) and writing velocity (respectively 1.623 cm/s and 1.723 cm/s; $F(1,74)=9.58$; $p<.01$). It has been shown that children perform longer cursive writing trajectories with somewhat higher writing velocities (Meulenbroek & Van Galen 1986). The question remains why the subjects realized slightly longer writing trajectories in the cursive than in the printed letter condition. An explanation may be that the cursive stimulus letters contained longer trajectories than the printed stimulus letters. Although the height of the bodies of printed and cursive stimulus letters was equal the actual trajectories of cursive stimulus letters were longer than of printed stimulus letters especially in the case of extenders (i.e., letters containing ascenders - *b, d, f, k, l, h* - and descenders - *f, g, j, p, q, y* -). Corpus-sized letters (i.e., *a, c, e, i, m, n, o, r, s, u, v, w, x, z*) were written with 1.9% longer writing trajectories in the cursive than in the printed letter condition while extenders were written with 5.8% longer writing trajectories in the cursive condition.

Response-initiation-time differences for separate letters

The upper graph of fig. 4 depicts the mean response-initiation time for each letter of the alphabet in the printed (open circles; dotted line) and cursive letter condition (closed circles; solid line). For all letters the mean response-initiation time in the printed is longer than in the cursive letter condition. The mean response-initiation-time difference between the printed and cursive condition for each letter is depicted in the middle graph of fig. 4. In this

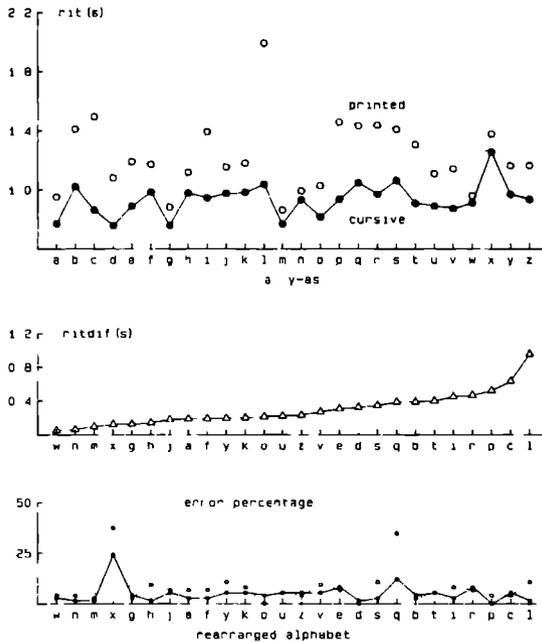


Figure 4. Upper graph: mean response initiation time (rit) per grapheme in the printed (dotted line) and cursive condition (solid line). Middle graph: Response-initiation-time difference (ritdif) per grapheme between printed and cursive letter condition. A rearranged order of the alphabet on the x-axis has been chosen according to an increasing ritdif-criterion. Lower graph: Error percentage in printed (dotted line) and cursive (solid line) letter condition as a function of the rearranged alphabet.

graph a rearranged order of the alphabet has been chosen according to an increasing response-initiation-time difference criterion. According to our assumptions these results reflect the time subjects need to perform a cognitive translation process from the graphemic to the allographic level. It appears from the analyses that the spatial ambiguous letters *b*, *d*, *p*, *q* need more time to be converted from the printed into the cursive form than the spatial unambiguous letters *a*, *g*, *k*, *s*. The mean response-initiation-time difference was 0.193 s (t -test $t=4.51$; $p<.01$). Further it appeared that the letters *b*, *d*, *p*, *q* which are spatially ambiguous along the vertical axis needed longer translation times than the letters *m*, *n*, *u*, *w* which are ambiguous along the horizontal axis. The difference in response-initiation times between these latter two groups of letters was 0.253 s ($t=4.58$; $p<.01$). This suggests that reversals of spatially ambiguous letters are mainly caused by mirror

reversions along the vertical dimension and not along the horizontal dimension. This result corresponds with the findings that in children as well as in adults up-down discrimination is superior to left-right discrimination (Flanders 1976). The middle graph also shows that letters with a relatively large number of allographs (*r, s, t*) need longer cognitive translation times than letters with only one allograph (*e, j, o*). The mean difference amounted to 0.146 s ($t=2.75$; $p<.01$). Finally this graph shows that contextual ambiguous letters (*b, g, i, l, o, q, x*) require longer cognitive translation time than contextual disambiguous letters (*a, e, f, k, h, s, z*). This difference amounted to 0.127 s ($t=3.32$; $p<.01$).

For each of the 75 subjects the correlation between response initiation time per letter and letter frequency was calculated in the printed and in the cursive letter condition. In the printed letter condition 28 positive and 47 negative correlations were found (sign-test: $p<.05$) with a mean correlation of $R_{xy} = -.061$. In the cursive condition 17 positive and 58 negative correlations were found (sign-test: $p<.01$) with a mean of $R_{xy} = -.116$. The lower graph of fig. 4 shows that the infrequent letters *x* and *q* were incorrectly performed in many cases. The total error percentage was 8.1 % in the printed and 4.9 % in the cursive letter condition. Apart from these two letters it appeared that a positive correlation of 0.21 was present between response-initiation-time differences of the printed and cursive letter condition and total number of incorrectly performed trials. These results show that in general letter frequencies influenced response initiation time significantly in such a manner that more frequently used letters were faster retrieved from memory than less frequently used letters.

Analysis of writing trajectories

Motoric complexity of cursive graphemes

Fig. 5 depicts the realized writing velocities (upper graph), writing dysfluency data (middle graph) and the maximum curvature data (lower graph). The letters depicted on the x-axes of the graphs of fig. 5 were rearranged according to a decreasing writing speed criterion. Negative correlations were found between the velocity and dysfluency measurements ($R_{xy}=-0.789$; $p<.01$) and between the velocity and maximum curvature measurements ($R_{xy}=-.415$; $p<.01$). A positive correlation was found between the dysfluency and the maximum curvature measurements ($R_{xy}=.387$; $p<.01$). According to our assumptions the rearrangement of the alphabet on the x-axes of the graphs in fig. 5 reflects an order of increasing motoric complexity of cursive graphemes. The most complex letters were the letters *r*

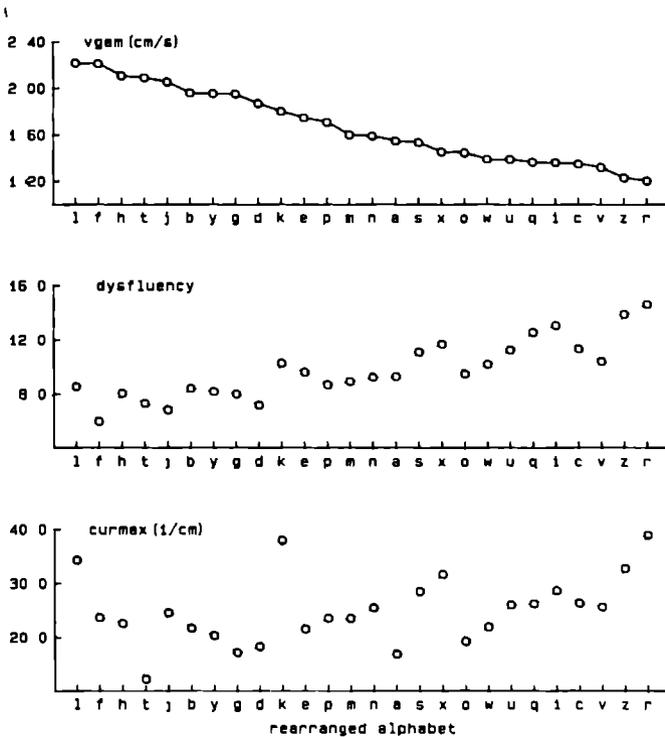


Figure 5. Mean writing velocity (vgem - upper graph), writing dysfluency (middle graph) and maximum curvature (1/cm; lower graph) as a function of the letters of the alphabet. The *rearranged alphabet* on the x-axes reflects an order of decreasing writing velocities.

and z. These letters are the only two letters of the alphabet of the writing curriculum containing horizontally oriented wave-form segments. This result corresponds with earlier findings concerning the motoric complexity of wave-like patterns (Meulenbroek & Van Galen 1986). With the exception of the letter *q* all extenders are written with higher writing velocities than corpus-sized letters. It appears that extenders are easier to write than corpus-sized grapheme segments, probably because the longer trajectories of ascenders and descenders elicit faster and more fluently performed writing movements. Data which justify this interpretation can be observed in the lower two graphs of fig. 5. The letters *k*, *s* and *x* are relatively dysfluent and written with high maximum curvatures. The letter *k* is a relatively difficult letter to write because of the combination of an ascender and a very demanding body with sudden changes in rotational direction. The letters *s* and *x* also contain changes of rotational direction within one stroke and are

therefore also relatively complex.

Developmental aspects

We reported about the developmental aspects of the data of the present experiment in Meulenbroek and Van Galen (1988). It appeared that there was a significant main effect of grades on response-initiation times ($F(4,70)=7.46$; $p<.001$) with a linear decreasing trend ($F(1,70)=2.31$; $p<.001$). No interaction was found between grades and stimulus presentation mode on response-initiation time. Significant decreasing quadratic age trends were found in movement time, velocity, maximum curvature and dysfluency data, again with no significant interactions with stimulus presentation mode. With increasing age the maximum curvature of grapheme segments decreased whereas the minimum curvature increased. This means that young children performed cursive graphemes with relatively straight trajectories and sudden curvature changes whereas older children realize medium curved trajectories instead of straight segments and avoid strong curvature changes. These results were extensively discussed in Meulenbroek and Van Galen (1988).

Conclusions and educational implications

In this experiment primary school children wrote single cursive graphemes under speed instructions after presentations of printed and cursive letters. An analysis of response-initiation-time differences between the printed and cursive letter condition revealed a number of factors which, according to our assumptions, influenced the duration of a cognitive translation process from the graphemic to the allographic level. These factors were : a) spatial ambiguity of allographs, b) number of lower-case allographs of a grapheme, c) contextual ambiguity of allographs and d) letter frequency. Although no attempt was made to determine the weight with which each factor contributes to the overall complexity of a letter, our data showed that spatial ambiguous letters, letters having many lower-case allographs, context-dependent letters and seldomly used letters required relatively long preparation intervals. The aforementioned complexity factors might be called within-letter-mode factors. It might be argued that another complexity factor, the between-letter-mode factor similarity, could have influenced the response-initiation-time differences between the printed and cursive letter conditions. One might expect a small response-initiation-time difference when the printed and cursive form of a letter are similar. However, the reverse appears to be the case. The data show that response-initiation-time differences are relatively large with letters of which the printed and cursive form are similar (*c, i, q*)

and relatively small with letters of which the printed and cursive form are dissimilar (*a, f, g*). The mean difference in translation time between these two groups of letters was 0.239 s ($t=4.20$; $p<.01$). This result shows that the distinctiveness of a letter form, within as well as between letter modes, is an important aspect determining the ease with which the letter is recognized and retrieved from memory. It might also be argued that the ecological validity of the present experiment would have been higher if not only a visual presentation mode was used. Teachers normally introduce the visual form of a letter together with its acoustical form. The fact that letters were not verbally presented in this experiment might have been the reason for the relatively long response initiation times. However, it must be recognized that in writing education a reasonable amount of time is spent by pupils in practising the writing of letters without verbal assistance of the teacher. In these situations pupils cannot rely on acoustical information, and visual aspects of the task become more important. Secondly, our experimental procedure has ecological validity for computer assisted writing education which presently is based more on visual than on acoustical instructions (Plamondon, Suen & Simner, in press)

The motoric complexity of cursive graphemes was investigated by comparing the writing velocities, dysfluency measurements and the maximum curvature data of the produced letters of a cursive alphabet. It appeared that the cursive graphemes *r* and *z*, two graphemes containing small, horizontally oriented, wave-like segments, were performed with the slowest writing velocity. Graphemes containing ascenders and descenders (i.e., extenders) were written relatively fast because these graphemes contain relatively long segments which can be produced with higher writing velocities as compared to more strongly curved corpus-sized graphemes which require slower writing movements. It should be mentioned that the exact form of the trajectories of cursive letters is culture as well as curriculum dependent.

Educational implications

The results of this experiment offer us an opportunity to advise developers of reading and writing curricula to take into consideration the cognitive complexity factors of letter forms when they determine the order in which single letters appear in the curriculum. When we let this sequence be determined by complexity, i.e., first the simple letters and then the more complex letters or when printed and cursive letters are introduced simultaneously, the order which is depicted in the middle graph of fig. 4 might be recommended. This recommendation is especially relevant for those countries in which the first three or four years of writing education

consist of writing printed letters. When a curriculum is being developed solely for learning cursive handwriting the order which is depicted in fig. 5 might be a sequence which guarantees that motorically less complex cursive letters precede the motorically more complex ones. Furthermore the results of this experiment might be used for minor but motorically important changes in cursive letter forms themselves to ensure that they elicit compatible, fast and fluent writing movements. The positive correlation between realised curvature and writing velocity of the produced cursive writing segments suggests that cursive letter forms should not contain unnecessary high curvatures and sudden curvature changes within the up and downgoing letter segments. Finally the results showed that cursive letters should not contain straight trajectories because cursive grapheme segments were produced by older children with slightly curved movements instead of straight lines. A few examples for cursive letter improvement are shown in fig. 6.

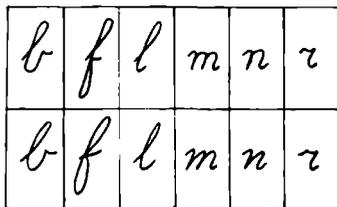


Figure 6. Examples of the improvement of cursive letter forms on the basis of the reduction of unnecessary and strong curvature in letter segments. The upper row represents original models of cursive letter forms as used in a Dutch writing curriculum. The lower row represents improvements of these forms as far as straight trajectories are replaced by slightly curved trajectories and strong curvature changes within the up and downgoing segments have been avoided.

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THE ACQUISITION OF SKILLED HANDWRITING: DISCONTINUOUS TRENDS IN KINEMATIC VARIABLES*

Ruud G. J. Meulenbroek and Gerard P. Van Galen

The inference of movement control strategies from recorded writing signals is illustrated by presenting the recordings and corresponding absolute velocity profiles of the first attempts in writing an unfamiliar grapheme by an adult subject. A number of kinematic variables derived from these recordings are discussed and used as dependent variables in an experiment. Primary school children from grade two to six wrote the letters of a cursive alphabet in a paced writing task. Movement time, absolute velocity, curvature and writing dysfluency measurements of produced grapheme segments were measured. The changes in these kinematic variables during primary school revealed a discontinuity in writing development. The results show that during the acquisition process a temporarily decline in performance measures can be observed as a result of feedback controlled movement strategies. During the learning of the handwriting skill the feedback controlled movement strategy is gradually replaced by an open loop movement strategy.

INTRODUCTION

Inferring control strategies from recorded writing movements

In the early stage of learning a skill, feedback is assumed to shape the relevant schema (Schmidt 1975; 1976) or representations of the movement patterns involved while in a later stage feedback processes have a monitoring function and do not interrupt the execution of planned movements anymore. The detection of movement corrections and interruptions is often used as a technique to investigate how skilled movements are learned, controlled and coordinated. Clear examples of the inference of control strategies from recorded movements are the studies of Hay (1979, 1984) and Von Hofsten (1979, 1980). By analyzing the displacement functions of aimed reaching movements Hay and Von Hofsten demonstrated that 5 year-old children used an open-loop ballistic movement strategy, 7-year-old children used a closed-loop feedback controlled movement strategy and 9- and 11-year old children

* *Cognition and action in skilled behaviour* (1988), A.M. Colley and J.R. Beech (Eds.), Elsevier Science Publishers B.V., North Holland (pp. 273-281).

managed to integrate these two control strategies.

In comparison with discrete aiming or pointing tasks, cursive handwriting is a more complex skill which can be characterized by a continuous flow of precise, distally performed, curved movements. Nevertheless, handwriting is often considered as a series of composite aiming movements (e.g., Wann 1986; Meulenbroek & Van Galen 1986). When writing movements are performed skillfully, each aiming movement corresponds with an upstroke or a downstroke of a grapheme. Strokes can be straight or curved trajectories. An illustration of this type of analysis of handwriting is depicted in Fig. 1.

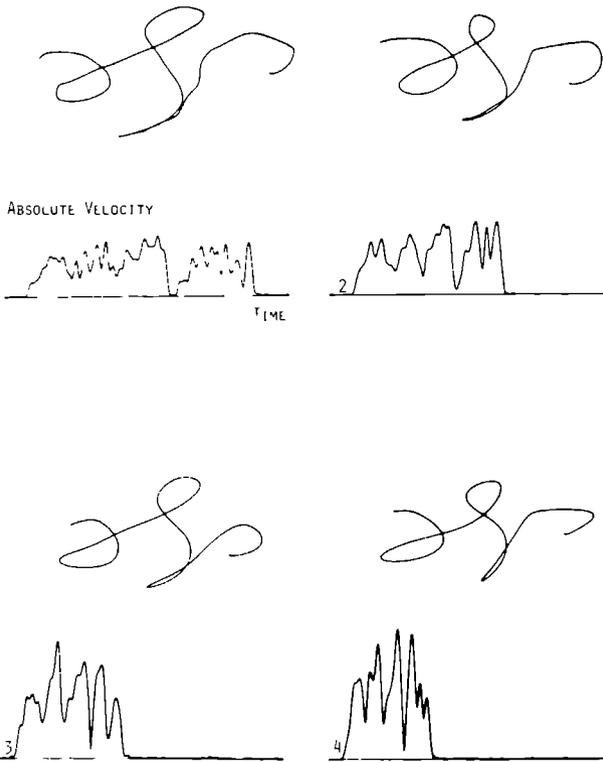


Figure 1. The first four attempts in writing an unfamiliar grapheme by an adult subject. Writing movements were recorded with a sample frequency of 105 Hz and filtered with a low-pass filter of 12 Hz. Below each recorded writing sample the corresponding absolute (tangential) velocity function is depicted.

An adult subject was asked to study an unfamiliar grapheme carefully for a few minutes. Then he was asked to write the grapheme a number of times without being able to see the original model. His writing movements, performed with a normal ballpen on standard writing paper, were recorded by means of a Calcomp digitizer and a PDP-11/45 computer, with a sample frequency of 105 Hz. The recorded signals were filtered with a low-pass filter of 12 Hz and displayed for inspection. Fig. 1 depicts the first four attempts of the subject writing the unfamiliar grapheme. Below each attempt the absolute (tangential) velocity of the pen-point movements as a function of time is depicted. Typical changes can be observed in these velocity profiles: 1) the time needed to perform the unfamiliar grapheme decreases with the number of attempts (the velocity profile becomes narrower), 2) the highest velocity within each attempt increases and 3) the number of velocity-peaks starts to correspond with the number of up- and downstrokes which are needed to perform the grapheme. The grapheme recordings show furthermore 1) a decrease in writing size and 2) sudden curvature changes within up- and downgoing parts of the grapheme which are present in the first two, but absent in the last two, attempts. From these aspects of the recorded writing movements and their corresponding tangential velocity profiles we deduce that the first attempt was probably controlled by a closed-loop movement strategy resulting in slowly performed, large-sized, frequently interrupted movements and that the fourth attempt was controlled by an open-loop movement strategy resulting in fastly performed, somewhat smaller and uninterrupted ballistic movements. However, this deduction must be made with care because there is no information in these recordings which reflects the sources and time characteristics of involved kinaesthetic and/or visual feedback processes.

The writing movements of young children show a large number of interruptions within up- and downstrokes of produced graphemes. Fig.2 contrasts graphemes (and corresponding velocity profiles) performed by a 7-year old child (on the left-hand side) with those performed by an adult (on the right-hand side). The child produced the writing patterns with a large number of motoric impulses whereas the adult produced in both patterns five motoric impulses to realize the five strokes of each pattern.

The acquisition of cursive writing movements

In a study of repetitive writing behaviour of first, second and third-grade primary-school children (Meulenbroek & Van Galen 1986) we studied the microstructure of the stroke production process from a developmental viewpoint. We found that the acquisition of the writing skill probably occurs in discontinuous stages in a similar way as was described for

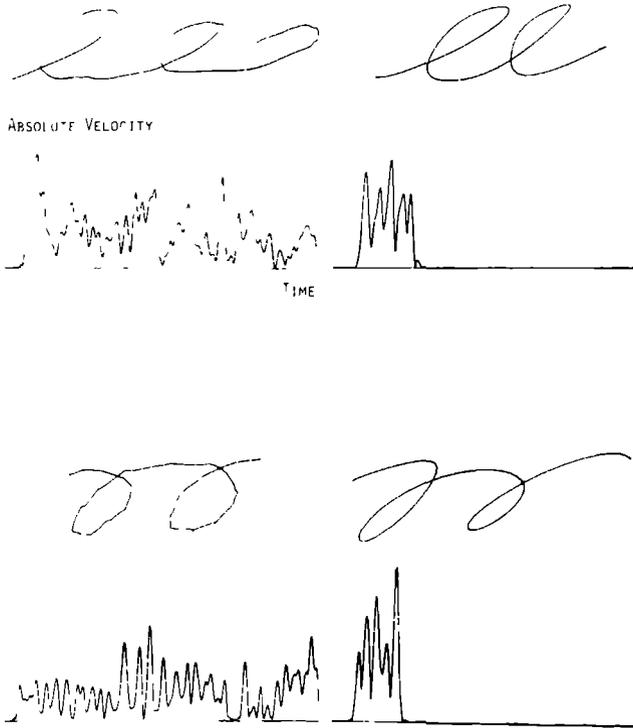


Figure 2. Two repetitive writing patterns with corresponding absolute (tangential) velocity functions performed by a 7-year old child (left-hand recordings) and an adult (right-hand recordings).

aimed reaching tasks by Hay (1979, 1984). In our study the youngest children performed relative fast movements with little interruptions. The writing performance of second-grade children was slower and showed frequent interruptions. Grade three children regained a moderate writing speed and their frequency of movement interruptions decreased. In the following experiment we tried to verify these observations in a letter writing task performed by primary school children.

METHOD

Subjects

Seventy-five normal children from an ordinary urban primary school in Nijmegen served as subjects in this experiment. They were selected from

grades two to six, each selected group consisting of fifteen children. The mean age and range of ages for the five groups given in years and months were respectively: 8;0 (7;4-9;0), 8;10 (8;5-9;6), 10;0 (9;5-10;6), 11;1 (10;7-11;9) and 12;0 (11;5-12;9).

Procedure and apparatus

All subjects performed the experiment in an airconditioned, moderately lit, sound-proofed van. Each subject was seated on a school chair in front of a school desk both adjusted to the body size of the subject. Visual stimuli were projected on the writing surface by means of a slide-projector and a special mirror. The projection contained no double reflections. On each slide the contours of two adjacent, horizontally placed bright squares and one bright letter was depicted. The mirror above the schooldesk was placed in such a manner that the projected body of the smallest letters was 5 mm. The letter was always presented in the centre of the left-hand square. The subject had to write the correct cursive grapheme in the centre of the right-hand square. Left-handed subjects were allowed to write the grapheme to the left of the stimulus-field.

The subject was instructed to write the correct cursive grapheme as soon and as fast as possible whenever a new letter was presented in the left-hand square. An Apple-2 microcomputer controlled the slide projection and the recording of the writing movements. The latter were sampled at a rate of 100 Hz by means of an Apple-2 XY tablet and a slightly thicker than normal ballpen which were both attached to the micro-computer. The XY tablet and the projected stimuli were rotated 10 degrees anti-clockwise for right-handers and 10 degrees clockwise for left-handers to ensure an optimal writing posture of the subject. The experimenter was seated on the right-hand side of the subject and observed the writing movements by means of a tv-monitor placed in front of him. This monitor could not be seen by the subject. After the subject had completed a grapheme the experimenter stopped the sampling period, which had a maximum duration of six seconds, and a high tone was presented as an indication for the subject to shift the non-ruled writing-paper (format A4) upwards to such a degree that the just written letter came to be situated above the two squares. An intertrial restperiod of about twenty seconds was used to store the latency and the sampled writing movements on a diskette.

Each subject performed two series of 26 trials in which each letter of the alphabet occurred once. In each series a different order of letters was used.

Data analysis

Data analyses were performed by means of a VAX-11/750 computer. Each

recorded grapheme was divided into up- and downstrokes by means of an interactive computer analysis system. A distinction was made between the entry and exit strokes of a grapheme and the strokes which made up the body of the letter itself. Because it was reasoned that in normal handwriting the movement kinematics of entry and exit strokes are influenced by preceding and following letters, these strokes were excluded from the analyses.

Of each grapheme segment (64 per alphabet) the following measures were calculated : duration, distance, mean and maximum velocity, minimum and maximum curvature and the number of absolute-velocity inversions per unit length. An example of the analysis of one record is depicted in Fig. 3.

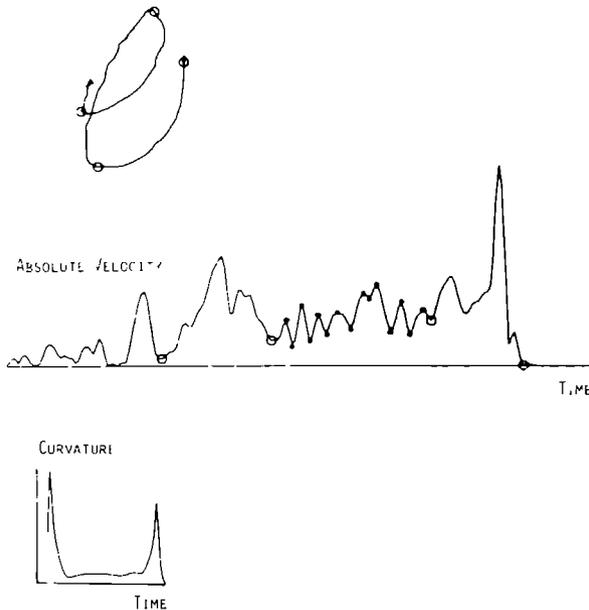


Figure 3. Example of the data analysis of one record. The grapheme *e* (cut in three segments; open circles) and the corresponding absolute velocity function of the writing movements (middle graph). Movement time, distance, velocity and writing dysfluency (i.e. number of velocity inversions - closed circles- per unit length) were calculated on the basis of the absolute velocity pattern. Curvature measurements of the central segment of the grapheme *e* were determined from the curvature function (lower graph) which was derived by dividing the angular and absolute velocity functions.

The curvature function of each grapheme segment was derived by dividing the angular and absolute velocity functions. This procedure is fully described by Maarse, Teulings and Bouwhuisen (1985). The number of absolute-velocity inversions per unit length (with exclusion of the velocity dips at the borders of the cut segments) was regarded to reflect the dysfluency with which grapheme segments were produced. It was reasoned that when during the production of a grapheme segment more than one inversion occurs in the absolute-velocity pattern, motoric impulses interrupt the ballistic manner in which a handwriting stroke is normally produced (Meulenbroek & Van Galen 1986).

RESULTS

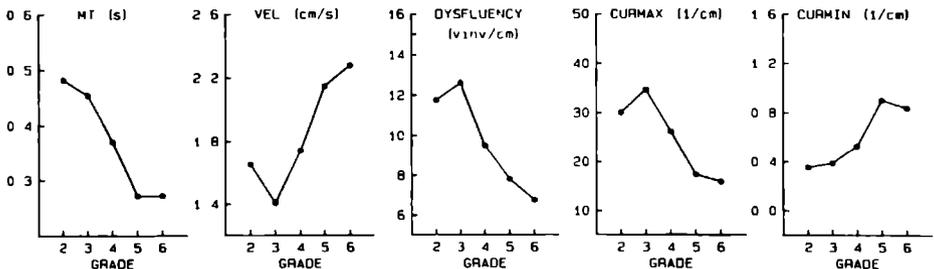


Figure 4. Changes in the analyzed kinematic variables of grapheme segments as a function of grades. MT = movement time (s); VEL = Mean Writing Velocity (cm/s); DYSFLUENCY = Number of Velocity Inversions per cm; CURMAX = Maximum Curvature (1/cm) and CURMIN = Minimum Curvature (1/cm).

Fig. 4 depicts the changes of the different kinematic variables as a function of grades. The leftmost graph depicts the mean movement time of the analyzed grapheme segments. A decreasing trend can be observed which levels off at grade five. Trend analysis revealed a significant linear trend ($F(1,70)=65.28$; $p<.001$) as well as a significant cubic trend ($F(4,70)=4.65$; $p<.05$). The second graph shows significant linear and cubic trends in the mean writing velocity data (respectively: $F(4,70)=15.21$; $p<.01$ and $F(4,70)=4.32$; $p<.05$). At first writing velocity decreases from grade two to three. From this grade on writing velocity increases up to grade six. Similar results were found in the maximum velocity data. The dysfluency data are depicted in third graph of Fig. 4. Grade three children wrote the cursive

letters with the highest number of velocity inversions. From grade three to six a decrease of dysfluency is observed. Trend analysis revealed a significant linear trend ($F(4,70)=19.04$; $p<.001$). The maximum curvature of the grapheme segments is depicted in the fourth graph of Fig. 4. Again a discontinuous developmental trend can be observed. The linear ($F(4,70)=11.91$; $p<.001$) and cubic trend ($F(4,70)= 7.20$; $p<.01$) were significant. While the maximum curvature of grapheme segments decreases from grade three to grade six the minimum curvature data show a reversed developmental trend (rightmost graph of Fig. 4). The minimum curvature increases linearly from grade two to grade five ($F(4,70)=30.60$; $p<.001$).

DISCUSSION

In the experiment primary school children wrote single cursive graphemes under speed instructions after visual presentations of single letters. The acquisition of the handwriting skill was investigated by analyzing a number of kinematic variables of produced cursive grapheme segments. Evidence was found for a discontinuity in development of the writing skill during primary school. Our observations correspond with earlier findings of Hay (1979, 1984) and Von Hofsten (1979, 1980) concerning the development of other motor skills and those of Meulenbroek and Van Galen (1986) concerning repetitive writing behaviour. A decline in performance was observed from grade two to grade three. Writing velocity decreased, movements became more dysfluent and large curvature changes during the stroke production process occurred more often. The changes in these kinematic variables are probably due to the use of visual and kinesthetic feedback processes which interrupt the normally smooth production of grapheme segments. Since no attempt was made in this experiment to determine the shape accuracy of the produced graphemes it is not clear whether 9-year old children tried to achieve higher standards. Another explanation of the discontinuity in writing development has been put forward by Wann (1986). Wann stated that at this point in the acquisition of the writing skill, writing pressure could be responsible for the dysfluency of stroke production. When writing pressure is high the increase of the number of inversions in the absolute velocity profile not necessarily reflects the involvement of feedback processes. Therefore, in future studies pen-point pressure and shape accuracy should be taken into consideration, together with kinematic variables which reflect the underlying control strategies, to make the inference of control strategies from recorded writing signals more valid.

From grade three to six writing performance became gradually faster, more fluent and more efficient with regard to realized curvatures. As far as the curvature measurements are concerned it appeared that older children wrote cursive graphemes with less straight grapheme segments and less dramatic curvature changes. The straight writing movements were replaced by slightly more curved movements, probably corresponding with the natural curvature of stationary movements of the hand and fingers (Maarse et al. 1986).

The point at which performance temporarily declines during the development of motor skills seems to differ depending on the skill. With reaching the decline was observed in 7-yr.-olds (Hay 1979) as well as with drawing simple repetitive writing patterns (Meulenbroek & Van Galen 1986). In our experiment concerning cursive handwriting we observed a decline in performance in grade three children with a mean age of ten years. It seems that as the skill which has to be mastered becomes more complex the discontinuity in the acquisition process is observed at a later age.

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Chapter 5

The production of bigrams

THE PRODUCTION OF CONNECTING STROKES IN CURSIVE WRITING: DEVELOPING CO-ARTICULATION IN 8 TO 12 YEAR-OLD CHILDREN*

Ruud G. J. Meulenbroek and Gerard P. Van Galen

In this paper it is argued that connecting cursive letters is a motorically distinct and demanding aspect of handwriting. In addition, the development of letter connection behaviour is investigated by means of an experiment in which 8 to 12 year-old children performed a standardized writing task. The subjects wrote combinations of two letters in which connecting strokes of varying forms had to be realized. Three analysis techniques were used to investigate the distinctiveness and development of letter connection behaviour. Movement kinematics, frequency spectra and spatial variabilities of upstrokes of identical orientation between and within letters were analysed. The results showed consistent kinematic and spectral differences between connecting and within-letter strokes. A smooth connecting strategy developed continuously with age, whereas discontinuous developmental trends were present in the kinematics of within-letter strokes. To verify the specific motoric status of connecting trajectories the spatial variability of both types of strokes was studied in adult handwriting samples.

INTRODUCTION

Cognitive models of the production of handwriting (Ellis 1982; Keele 1981; Van Galen, Meulenbroek & Hylkema 1986) have paid little attention to a motor activity which is inherent in most adult handwriting, viz., the fluent connection of successive letters within words by means of smooth connecting strokes. Recently, we presented a model in which handwriting is described as a typically concurrent and multiple task (Van Galen et al. 1986). According to this model connecting the exit stroke of a letter to the entry stroke of a next letter can be seen as a motorically distinct and demanding aspect of handwriting. We assume that the production of smooth traces between successive letters is different from the execution of retrieved letters, because it is unlikely that connecting strokes are represented as fixed,

* *Computer recognition and human production of handwriting*, R. Planondon, C.Y. Suen & M.L. Simner (Eds.), Singapore: World scientific publishing Co., (in press).

abstract memory codes. The exact form of a connecting stroke is dependent on the actual pair of letters given. Theoretically there are 26×26 different pairs of lower case letters in cursive writing. The actual number of different connecting strokes is lower, because of linguistic constraints and shared typologies of exit and entry strokes of letters throughout the alphabet. However, the number of possible letter connection trajectories is still very large and it is therefore unlikely that the motor system prepares these strokes by means of retrieval processes from an abstract long term store. Instead, we assume that the connecting stroke is produced on a real time computational basis in such a manner that a best fit to the ideal connecting path between an exit and an entry stroke is obtained. The generation of this best fit may be seen as an essential and individual part of the handwriting production process.

In the more biophysically oriented approaches to handwriting, strokes have mostly been studied without considering whether they were located within or between letters. Differences between up and down strokes have been investigated by Maarse and Thomassen (1983) but a distinction between upstrokes between letters and upstrokes within letters was not made. In the models of Hollerbach (1979) and Morasso & Mussa Ivaldi (1982) some form of co-articulation between successive strokes is assumed, but again no distinction is made between connecting and within-letter strokes.

In the present experiment, we tested the distinctiveness of letter connection behaviour as well as the development of a smooth letter connection strategy in 8 to 12 year-old children. A total of 75 children wrote combinations of two letters in which connecting trajectories of varying forms had to be realized. The choice of letter combinations used in our experiment was based upon a classification of entry and exit strokes of the lower-case letters of the alphabet which was used to teach the subjects cursive handwriting. We assumed that two aspects of connecting strokes determine the ideal form of the trajectory between two letters: (1) the location of the starting point of the connecting stroke relative to the local lineature, and (2) the direction of rotation of the connecting stroke itself. We chose 28 letter combinations in which the connecting strokes started below, at or above the baseline of writing and in which these strokes contained different directions of rotation (see Figure 1).

Three analysis techniques were used to investigate letter connection behaviour. Movement time, distance and writing dysfluency measures were determined in a kinematic analysis, median frequencies of average amplitude frequency spectra of tangential velocity profiles were analysed in a spectral

ne							
	e	b	t	w	d	m	r
n	<i>ne</i>	<i>nb</i>	<i>nt</i>	<i>nw</i>	<i>nd</i>	<i>nm</i>	<i>nr</i>
v	<i>ve</i>	<i>vb</i>	<i>vt</i>	<i>vw</i>	<i>vd</i>	<i>vm</i>	<i>vr</i>
f	<i>fe</i>	<i>fb</i>	<i>ft</i>	<i>fw</i>	<i>fd</i>	<i>fm</i>	<i>fr</i>
g	<i>ge</i>	<i>gb</i>	<i>gt</i>	<i>gw</i>	<i>gd</i>	<i>gm</i>	<i>gr</i>

Figure 1. The top of the figure shows an example of a projected manuscript letter pair. The matrix contains the 28 cursive bigrams which had to be produced in the experiment. Beside the rows and above the columns the manuscript letters are depicted which were used as first and second stimulus letters respectively.

analysis and spatial variabilities of strokes were analysed in a spatial analysis. We recently reported (Meulenbroek & Van Galen 1986; 1988) that kinematic parameters of produced strokes, combined with analyses of frequency spectra, can be used to establish the motoric demands of writing tasks and that the number of absolute velocity inversions within strokes reflects the dysfluency of writing. The latter measure revealed systematic developmental changes reflecting the differential use of open and closed loop control strategies at different stages in the acquisition of cursive handwriting.

Our third analysis technique concerned the spatial variability of strokes. With increasing age, handwriting becomes more and more individual. Therefore, it can be expected that the spatial differences of comparable strokes produced by different subjects will increase with age. According to our assumptions this increase of between-subject spatial variance should be larger for connecting strokes than for within-letter strokes. Moreover, if in handwriting a letter-connection strategy is superimposed upon motor program retrieval processes, this would imply that connecting strokes should be more variable than within-letter strokes (Teulings, Thomassen & Van Galen 1986). The within-subject spatial variability of replications of identical

strokes should be larger for connecting than for within-letter strokes. This hypothesis was tested in a control experiment with adult subjects.

We can summarize our predictions as follows. In order to determine the distinctiveness of letter connection behaviour in cursive writing we predicted that writing trajectories which are located between successive letters are motorically more demanding than comparable writing trajectories located within cursive letters. This should be reflected by a longer movement time, writing distance and greater writing dysfluency for between-letter strokes than for within-letter strokes. In addition we predicted that the exact form of between-letter strokes should differ more between subjects than within-letter strokes and that with replications of one cursive bigram by a subject, the upstrokes between letters should be more variable than the upstrokes within letters.

METHOD

Subjects

Seventy-five normal children from an ordinary, urban, primary school served as subjects in the experiment. They were randomly chosen from grades two to six, each group consisting of fifteen children. The mean age and range of ages for the five groups given in years and months were respectively: 8;0 (7;4-9;0), 8;10 (8;5-9;6), 10;0 (9;5-10;6), 11;1 (10;7-11;9) and 12;0 (11;5-12;9). Of all subjects 31 were boys and 44 were girls. Nine subjects were left-handed. Eight right-handed, adult subjects participated in the control experiment described below.

Procedure and apparatus

The experiment was conducted in an airconditioned, sound-protected van. Each subject, tested individually, was seated in front of a desk adjusted to the size of the subject. The stimuli consisted of 28 pairs of manuscript letters chosen to represent the various connection types discussed above (see Figure 1). Using a slide-projector, each pair of letters was projected via a special reflecting mirror (that prevented double reflections) onto the writing surface of the desk. At the same time as a letter pair was projected the contours of two adjacent, horizontally placed bright squares were projected. The projected letter pair was always situated in the left-hand square. The height of the projected image of corpus-sized letters was 5 mm while the projected image of each square measured 30 mm x 30 mm. As soon as the image of each letter pair appeared on the desk the subject was asked to write (as fast as possible) the corresponding cursive version of the letter pair, or bigram, in

the centre of the blank square without lifting the pen. Left-handers were asked to write the bigram to the left of the projected letter pair. An Apple-2 microcomputer controlled the randomized slide projection and the recording of the writing movements. These were sampled at a rate of 100 Hz by means of the Apple-2 XY tablet and a slightly thicker than normal ballpoint pen. The XY tablet and the projected letters were rotated 10 degrees counter-clockwise for right-handers and 10 degrees clockwise for left-handers to ensure an optimal writing posture for each subject. After the sampling period, which had a maximum duration of six seconds, a tone was used to inform the subject to move the writing paper upwards thereby exposing a clean writing surface in preparation for the next pair of letters to appear on the desk. An intertrial restperiod of about twenty seconds was used to store the sampled writing movements on a diskette.

Control experiment

Eight adult subjects wrote a word of six letters containing a double *u* at the fourth and fifth letter position (like in the word *immuun*) 12 times. Words with a double *u* were chosen because the connecting upstroke between the letters *u* is identical to the within-letter upstroke within a letter *u*. Six times the subjects were not able to see their writing hand. We predicted that the within-subject spatial variability of replications of the upstroke between the letters *u* would be more affected by this experimental manipulation than the within-subject spatial variability of the within-letter upstrokes within the second letter *u*. Writing movements were recorded at a rate of 105 Hz, in trials of 5 seconds, by means of a Calcomp digitizer and a PDP-11/45 computer.

Data analysis

Data analyses were performed on a VAX-11/750 computer. Each recorded signal was first digitally filtered with a high cut-off frequency of 12 Hz. Subsequently the vertical displacement function was derived, displayed and used in an automatic search-procedure to isolate the first upstroke of the body of the first letter and the connecting upstroke between the two letters. Connecting strokes and within-letter strokes were comparable with regard to movement orientation.

Movement parameters and dysfluency

Of each selected stroke the absolute (tangential) velocity pattern was derived and displayed. The following measures were then calculated: movement time (MT), distance (DIST), number of inversion points in the absolute velocity

pattern (#VINV), number of inversion points per unit of time (#VINV/S) and per unit of distance (#VINV/CM). An example of an analysis of one stroke is depicted in Figure 2.

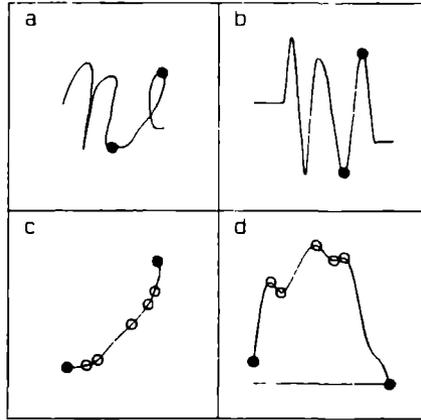


Figure 2. An example of the analysis of one stroke. The filtered XY trajectory of the pen is depicted in panel a. The corresponding Y displacement function is depicted in panel b; closed circles indicate the beginning and end of the connecting stroke. This stroke is displayed in panel c and the corresponding absolute velocity function in panel d. The open circles represent the inversion points in the absolute velocity pattern. The same procedure was used for selecting and analyzing the first upstroke of the corpus of the first letter.

The medians of the dependent variables of the 28 replications per subject were entered into analyses of variance and trend analyses. The SPSS-program MANOVA was used with a repeated measures design with Age Group as the between-subjects factor and Stroke Identity (between versus within-letter strokes) as the within-subjects factor.

Amplitude frequency spectra

Amplitude frequency spectra of the unfiltered absolute velocity patterns of the written bigrams, the between, and the within-letter strokes were analysed separately. For each individual spectrum the frequency at which 50% of the total power was transgressed was determined. The median frequencies were entered into the MANOVA procedure as described above. Each spectrum was then normalized for its total power between 0 and 50 Hz. By averaging the normalized spectra, the mean spectra of the bigrams, the between and the within-letter strokes were determined for each age group and displayed for inspection.

Spatial variability

The between-subject spatial variance of between and within-letter strokes of a bigram were determined separately for each age group according to the following procedure. Each of the 15 strokes, produced by the 15 Ss in a given age group, was rotated to a standard orientation of 45 degrees and normalized for its size and duration. Of each normalized stroke the distance to the average stroke of these 15 strokes was calculated according to a procedure which is similar to one procedure described by Maarse (1987). The mean distance of the 15 strokes to the average stroke was considered to reflect the between-subject spatial variance. An illustration of this procedure is depicted in Figure 3.

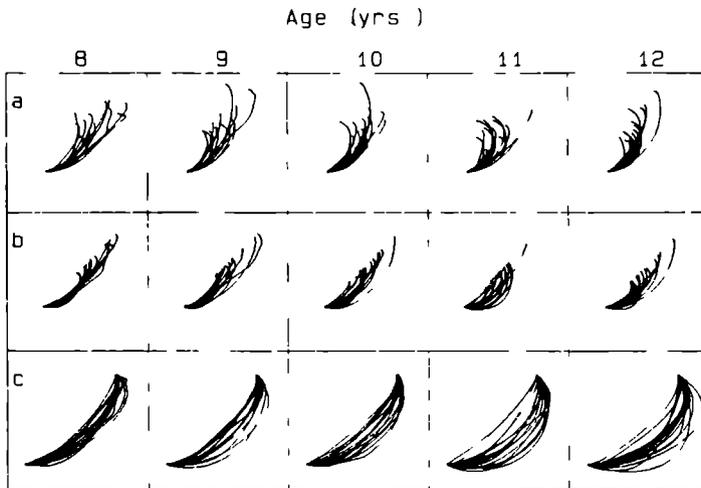


Figure 3. An example of the procedure used to determine the between-subject spatial variance of strokes. Columns represent age groups. In the first row (a) the filtered XY trajectories of connecting strokes between a bigram (*ne*) are depicted, in the second row (b) these strokes are rotated to a standard orientation of 45 degrees and in the third row (c) a normalization of time and size has taken place. From these normalized strokes an average stroke was calculated after which of each stroke the distance towards this average stroke was calculated.

Spatial measures were entered into the MANOVA procedure as described above. In the control experiment the within-subject spatial variability of strokes was determined using the same procedure. The upstroke between the double *u* was selected as the connecting stroke and the upstroke within the second *u* was selected as the within-letter stroke. The spatial variabilities in the two visual conditions were determined separately.

RESULTS

The results of the MANOVA procedures and trend analyses for the three different analysis techniques are summarized in Table I. The various findings reported in this Table will be discussed under the appropriate section.

Table 1
Analyses of variance and trend analyses for
the three different analysis techniques.

Movement kinematics and writing dysfluency						
Variable	MANOVA Source	F	p	Trend Type	F	p
MT	Age	18.58	<.001	linear	71.76	<.001
	Stroke	164.04	<.001			
DIST	Age*Stroke	9.67	<.01	quadratic	15.67	<.01
	Age	2.26	n.s.	linear	6.45	<.05
	Stroke	178.60	<.001			
#VINV	Age*Stroke	0.38	n.s.			
	Age	8.50	<.01	linear	31.62	<.001
	Stroke	59.43	<.001			
#VINV/S	Age*Stroke	12.06	<.001	quadratic	21.47	<.01
	Age	3.50	<.05	linear	10.82	<.01
	Stroke	40.99	<.001			
#VINV/CM	Age*Stroke	4.86	<.01	quadratic	9.96	<.01
	Age	3.29	<.05	linear	12.20	<.001
	Stroke	32.57	<.001			
	Age*Stroke	6.22	<.001	quadratic	13.84	<.001
Median frequency of average amplitude frequency spectra						
Variable	MANOVA Source	F	p	Trend Type	F	p
MF	Age	23.79	<.001	linear	92.88	<.001
	Stroke	205.78	<.001			
	Age*Stroke	5.22	<.01	quadratic	11.28	<.01
Between-Ss spatial variance and within-Ss spatial variability						
Variable	MANOVA Source	F	p	Trend Type	F	p
Betw-Ss	Age	21.70	<.001	cubic	9.76	<.001
	Stroke	14.44	<.001			
	Age*Stroke	2.45	<.05	linear	8.64	<.01
With-Ss	Stroke	6.01	<.05			

Movement kinematics and writing dysfluency

Figure 4 contains the mean movement time, distance and dysfluency data for the between and within-letter strokes for each age group. By comparing the evidence in Table I with the material in Figure 4 it can be seen that movement time decreased with age, was longer for the between than for within-letter strokes (316 ms and 243 ms, respectively) and that age and stroke identity produced a reliable interaction. On the other hand, movement distance did not decrease significantly with age although it did show a decreasing trend. Furthermore, the between-letter strokes were longer than the within-letter strokes in all age-groups (0.590 cm versus 0.442 cm, respectively) and no interaction between age and stroke identity was found in movement distance. Finally, with increasing age writing became less dysfluent in that all three measures of writing dysfluency decreased with age. At the same time, though, the between-letter strokes were written more dysfluently than the within-letter strokes in all age groups in addition to which significant interactions between age and stroke identity were found in the dysfluency measures.

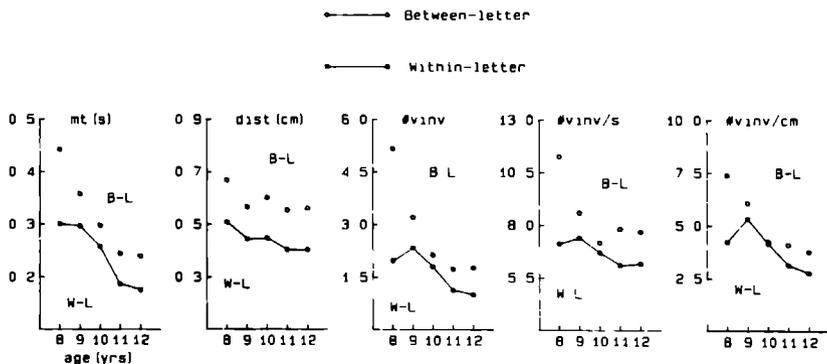


Figure 4. Mean movement time (MT), movement distance (DIST), number of inversion points in the absolute velocity pattern (#VINV), number of inversion points per second (#VINV/S) and per centimeter (#VINV/CM) of between-letter strokes (B-L) and within-letter strokes (W-L) per age group.

Amplitude frequency spectra

In general, the average amplitude frequency spectrum of absolute velocity patterns of adult handwriting shows decreasing contributions of frequencies ranging from 0.8 to 12.0 Hz, with a relatively powerful component around a frequency of 5.0 Hz. This component is the normal frequency in which

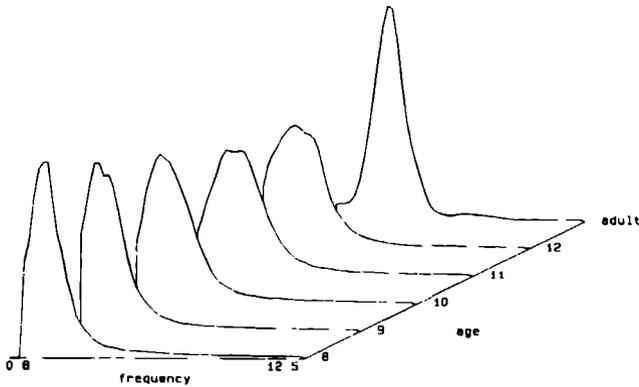


Figure 5. Semi three-dimensional plot of the average amplitude frequency spectra of the absolute velocity patterns of the written bigrams for children 8 through 12 years of age. For comparison an average spectrum of 50 bigrams written by an adult is also included.

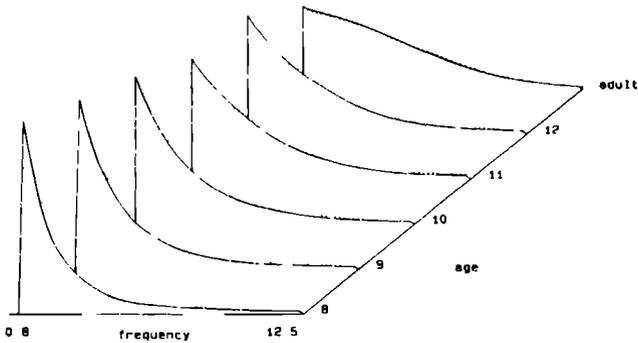


Figure 6. Semi three-dimensional plot of the average amplitude frequency spectra of the absolute velocity patterns of between-letter strokes (solid lines) and within-letter strokes (dotted lines) for children 8 through 12 years of age and an adult.

strokes are being produced (Teulings & Maarse 1984). The average spectra of the bigrams per age group are depicted in Figure 5. For reasons of comparison an average spectrum of fifty bigrams written by an adult is depicted. The spectra are depicted from 0.8 to 12.5 Hz, reflecting the relative distribution of 95% of the total power. The median frequencies steadily increased in the five age groups (1.76, 1.95, 2.15, 2.73, 2.93, respectively). For the adult samples this frequency had a mean value of 4.30 Hz. The average frequency spectra of between and within-letter strokes per age group

are depicted in Figure 6. The median frequencies of both between and within-letter strokes increased with age. For connecting strokes these frequencies were: 1.00, 1.28, 1.50, 1.90, and 2.00 Hz, for the five age groups. For within-letter strokes these frequencies had higher values: 1.47, 1.62, 1.82, 2.39 and 2.74 Hz, respectively. In these data an interaction was present between age and stroke identity.

Spatial variability

The between-subject spatial variance of connecting and within-letter strokes as a function of age groups are depicted in the left graph of Figure 7. As shown in this figure and in the outcome of Table I the spatial variance increased with age with a cubic trend, and even though it was measured after normalizing the strokes for size and duration, it was still found to be larger for the connecting than for the within-letter strokes. Moreover, an interaction between age and stroke identity was found in the analysis of variance. The increase in inter-individual spatial differences during primary school was significantly larger for the between-letter than for the within-letter strokes. In the adult handwriting samples of the control experiment, the within-subject spatial variability of replications (Figure 7; right graph), was larger in connecting than in within-letter strokes, especially in the non-visual condition. This result confirmed our hypothesis regarding the larger variability of connecting strokes as compared with within-letter strokes.

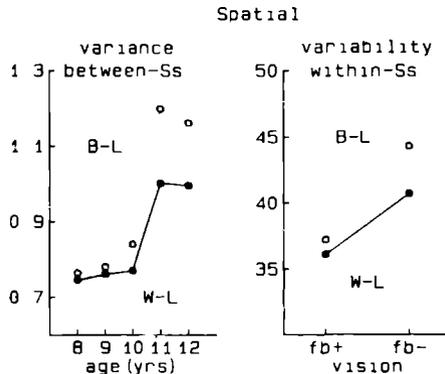


Figure 7. Left graph: the between-subject spatial variance of between-letter (B-L) and within-letter (W-L) strokes per age group. Right graph: the within-subject spatial variability of between-letter (B-L) and within-letter (W-L) strokes in the visual (fb+) and non-visual (fb-) condition of the control experiment.

DISCUSSION

The kinematic analysis revealed significant motoric differences between connecting (between-letter) and within-letter strokes. The time needed to perform connecting upstrokes was longer than the time needed to perform upstrokes within letters, but, connecting strokes were also larger than within-letter strokes. As such, these results are not sufficient to confirm our hypothesis with regard to the distinctiveness of connecting trajectories. However, connecting strokes were written more dysfluently than within-letter strokes, even after correcting our dysfluency measure for movement time and distance. This shows that the former strokes were motorically more demanding than the latter strokes. With increased age, the distance covered in both types of strokes, decreased to a similar degree, whereas the decrease in movement time and dysfluency measures was larger for connecting than for within-letter strokes. The differences between both types of strokes diminished during primary school. While continuous developmental trends were observed in the kinematic data of connecting strokes, discontinuous trends were present in these data of within-letter strokes. We reported earlier (Meulenbroek & Van Galen 1986;1988) that these discontinuous trends might reflect the use of an open-loop movement control strategy in an intermediate learning stage during which feedback is used to shape the relevant schema in handwriting. This developmental discontinuity was not present in the kinematic data of connecting strokes. A continuously improving strategy of co-articulation was observed during primary school.

Instead of measuring writing dysfluency, other authors have investigated the amount of jerk in movement, reflected by the rate of change in acceleration patterns (Nelson 1983; Wann & Jones 1986). We therefore re-analysed our data and determined the number of inversion points per second in the acceleration profiles. This analysis, however, showed the same pattern of results. A second control analysis was performed to test possible differences between left and right-handed subjects. The kinematic data of the 9 left-handed subjects were compared with the data of an equal number of right-handed subjects, matched with regard to age and sex, but no significant differences were found as a result of handedness. Although care was taken to select connecting and within-letter strokes with comparable movement orientations it might be argued that connecting strokes were more variable than within-letter strokes with regard to their direction of rotation. We therefore performed a third control analysis on a subset of bigrams in which the direction of rotation of both types of strokes was counterbalanced. This analysis showed the same pattern of results.

In the spectral analysis frequencies above 12 Hz were not neglected as was the case in the kinematic analysis. The exact form of the average spectrum of tangential velocity profiles of individual strokes is mainly determined by the duration and size of the strokes and by the degree to which the velocity profiles have a ballistic character. When strokes are being performed in short movement times and in a ballistic manner, the corresponding mean spectrum becomes broader and the median frequency increases. The median frequencies of the spectra of the connecting strokes were lower than the median frequencies of the spectra of the within-letter strokes. Connecting strokes were therefore performed less efficiently than within-letter strokes. With increasing age the median frequencies increased showing that stroke production became more efficient. These results confirm our hypothesis concerning the motoric distinctiveness of connecting trajectories and revealed the development of a smooth connecting strategy in 8 to 12 year old children.

We finally found that the inter-individual spatial differences of comparable strokes in children's handwriting, as well as the within-subject spatial variability in adult handwriting, was larger in connecting than in within-letter strokes. When connecting strokes are being produced by means of retrieval processes of memory codes from a long term store, the differences in the within-subject spatial variability in the control experiment should have been absent. The third analysis technique showed that even in adult handwriting connecting trajectories have a different motoric status than trajectories within cursive letter forms.

Besides showing that connecting cursive letters is a motorically distinct and demanding aspect of handwriting, the data from the present experiment revealed the growing mastery of the co-articulation of exit and entry strokes in handwriting during primary school.

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Chapter 6

The production of words

VARIATIONS IN CURSIVE HANDWRITING PERFORMANCE AS A FUNCTION OF HANDEDNESS, HAND POSTURE AND GENDER*

Ruud G.J. Meulenbroek and Gerard P. van Galen

Variations in cursive handwriting performance as a function of handedness, hand posture and gender were investigated by analyzing digitally recorded writing movements of ten righthanders, ten left-handed inverters and seven left-handed non-inverters who performed twelve writing tasks of increasing complexity. The analyses concerned writing speed, fluency, axial pen pressure, orientation of upstrokes and downstrokes and number and distance of pen-lift movements. Handedness and hand posture affected the orientation of strokes slightly. Female subjects exerted less axial pen pressure and wrote more slowly than male subjects. No further variations as a result of the subject variables were found in the kinematic performance measures of the upstrokes and downstrokes. It is concluded that left and righthanders produce cursive script evenly efficient as far as the realization of upstrokes and downstrokes is concerned. However, during the relocation of the writing hand moving from left to right along the lines of writing, non-inverted lefthanders lift the pen more often and along longer trajectories than inverted lefthanders and righthanders. Furthermore, inverted lefthanders show a tendency to write less wide than non-inverted lefthanders and righthanders. The results suggest that the inverted hand position may be considered as a functional adaptation to the writing task which, in our culture, progresses from left-to-right.

INTRODUCTION

Educational research on handedness and hand posture

Reviews by Askov, Otto and Askov (1970) and Peck, Askov and Fairchild (1980) have shown that little educational research concerning the effects of specific body positions on writing performance appeared in the 1960s and 1970s. Examples of this type of research are the studies of Reed and Smith (1962), Groff (1964) and Enstrøm (1962). Enstrøm showed that righthanders do not write more rapidly or legibly than lefthanders and he identified fifteen techniques of adjusting positions for handwriting used by lefthanders. After comparing 1,103 subjects on speed and neatness of writing samples Enstrøm

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found that left-handed school children using the non-inverted position (the writing hand below the line of writing) scored best and that this position should therefore be taught to lefthanders in the initial phases of writing education. The best of the inverted hand positions (the writing hand above the line of writing) was a position in which the writing paper was rotated counterclockwise and in which the wrist was turned on edge to permit maximum flexion. Enstrøm measured the quality of writing through the use of the Ayres scale (1912) and did not mention how the rate of writing was measured. The original report suggests that the subjects were given a writing task with speed instructions for a limited time span and that the size of the writing samples indicated the rate of writing. At present digital recording techniques offer us the opportunity to investigate the spatial and kinematic aspects of the movements of cursive handwriting in a more sophisticated and detailed way. In the present experiment variations in cursive handwriting performance as a function of handedness, hand posture and gender are re-examined by analyzing kinematic aspects of the digitized writing movements performed in various writing tasks by right-handed,

Inversion as adaptation to movement directions in handwriting

A number of authors (Enstrøm 1962, 1966; Wahl 1955, Herron 1980) have argued that the inversion of hand position can be interpreted as an adaptation to the necessity of writing from left to right. Levy and Reid (1978) argued against this assumption by stating that not all lefthanders use an inverted hand position. Moreover, they argued that a large fraction of left-handed Israelis, who write from right to left, invert their writing hand, whereas right-handed Israelis do not. The situation is more complex, however. In handwriting we must clearly distinguish between global progression movements at the level of the words positioned on the writing line and the local directions of up and downgoing pen movements which form the individual characters. Van Sommers (1984) showed that a remarkably consistent picture appears between Arabic, Hebrew and Latin script when the directions of the individual pen movements are plotted in polar plots. Although in Hebrew the characters are arranged from right to left, the strokes making up the characters are mainly produced from the top downwards and from left to right. Another example can be found in Chinese script. Traditional Chinese characters are arranged vertically down the page so that here the global movement applies to columns. In modern times Chinese characters are mainly written in horizontal lines, from left to right. Irrespective of these global directions, however, strokes of Chinese characters are generally made from the top downwards and from left to right. Only in Arabic script more leftward movement appears within characters but

there may be major differences in the positioning of the paper in Arabic writing (G. Noordzij; personal communication). This analysis suggests that when left-handed Israelis invert their hand position this might still be considered as an adaptation to the predominantly left-to-right direction along which the individual characters are formed. A complicating factor in these analyses is indeed the position in which the writer as an individual or as a member of a specific writing culture, places the writing paper on the table. This aspect may have influenced the findings reported so far. In the present experiment we will register the orientation of the writing paper adopted by each subject at the start of the experiment, and then standardize it throughout the remaining part of the experiment. We will further extend Van Sommers' (1984) strategy and plot the directions of upstrokes and downstrokes relative to the writing table as well as to the writing paper in order to investigate the directions along which righthanders and lefthanders produce the strokes in cursive script.

Anatomical realizations of movement directions

Wing (1978) argued that left-inverters produce downstrokes with wrist movements and upstrokes with simultaneous extension of thumb, index and second fingers. In a study with primary school children on the kinematics of the strokes of zig-zag movements we found that in righthanders the upstrokes of these patterns were performed more efficiently than the downstrokes (Meulenbroek & Van Galen 1986). We argued that upstrokes were realized by these subjects through abduction movements of the hand around the wrist joint whereas downstrokes were mainly due to flexion movements of the fingers. This interpretation corresponds with the findings of Maarse and Thomassen (1983), and Teulings, Thomassen and Maarse (in press). The latter authors have shown that wrist movements have a higher speed than finger movements, probably because the wrist joint has fewer degrees of freedom than the finger joints. If Wing's (1978) suggestion is correct, i.e. downstrokes by LI subjects are performed by wrist movements and upstrokes by finger movements, we should find more efficiently produced downstrokes than upstrokes. We will test this hypothesis by analyzing the kinematics of the upstrokes and downstrokes produced by lefthanders and righthanders in a zig-zag pattern.

METHOD

Subjects

Twenty-seven normal adults participated in the experiment. Handedness was classified on the basis of a 12-item questionnaire concerning hand preference

on unimanual tasks such as throwing, drawing and writing, etc. (after Annett 1967). Hand posture was classified according to the criteria of Levy and Reid (1978). The writing hand above the line of writing with the pen pointing to the bottom of the page, or below the line of writing with the pen pointing to the top of the page, was the criterion to classify the subject as an inverted or a non-inverted writer, respectively. Ten subjects, five female and five male, scoring 97.5 % of the unimanual tasks with the right hand and adopting a non-inverted writing posture were entered into the right-handed group with a normal hand posture (RN group). Another ten subjects, again five female and five male, performing 84.2 % of the unimanual tasks with the left hand and adopting an inverted writing posture formed the left-handed inverted group (LI group). Seven subjects, five female and two male, performing 90.5 % of the unimanual tasks with the left hand and writing in a non-inverted style, formed the left-handed non-inverted (LN group). Subjects applied voluntarily and were paid for participation in the experiment. Given the low incidence figures of non-inverted male writers (Annett 1967; Geschwind & Galaburda 1985) it was not surprising to find only two of them as subjects from a large population of students. For this reason the LN group contained fewer subjects than the RN and LI groups.

Experimental writing tasks and hypotheses

Twelve different writing tasks were selected of which the complexity gradually increased. The tasks enabled us to investigate whether variations in handwriting performance as a function of subject variables were located at the level of either the stroke, or the letter, or the word. On the basis of former experimental results (Van Galen et al. 1986; Meulenbroek & Van Galen 1988) effects of task complexity on the kinematics of the handwriting movements could partially be predicted. These predictions are subsequently discussed in the following paragraphs. The twelve tasks are displayed in Fig. 1.

Task 1: Ellipses

The first task consisted of continuously writing ellipses on top of each other. If progression movements in normal writing tasks are more difficult to realize for lefthanders than for righthanders, a task without such movements may be supposed to provide useful information on any differences in movement kinematics between the RN, LI and LN groups. There was no instruction as to the rotation direction of the ellipses. This was left open to the subject's preference. Some group differences in directional preferences of the movements in task 1 could be predicted on the basis of findings of Van Sommers (1984) and Thomassen and Teulings (1979). These authors showed

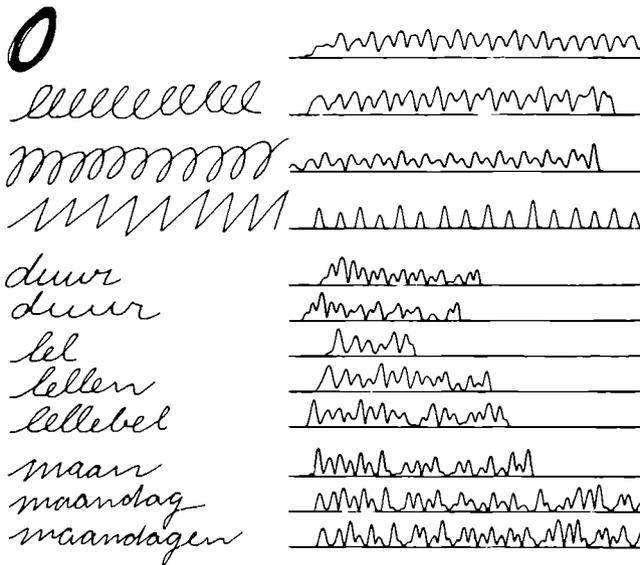


Figure 1 An overview of the twelve experimental writing tasks and samples of corresponding absolute velocity functions in the right half of the figure. The horizontal lines represent 4 seconds of time.

that in *drawing tasks* righthanders mostly prefer to produce counterclockwise and lefthanders clockwise movements.

Task 2 and 3: Rotating writing movements

The second and third task consisted of writing counterclockwise and clockwise rotating movements superimposed on a steady progression movement from left to right. In an earlier study we investigated the kinematics of these writing patterns in right-handed primary school children (Meulenbroek & Van Galen 1986) and found that counterclockwise movements were more efficiently produced than clockwise movements. This effect was attributed to the large amount of practice of counterclockwise movements because these are dominant in cursive handwriting (Thomassen & Teulings 1979). We therefore predicted that, although lefthanders might prefer clockwise rotations in task 1, task 2 would still be performed more efficiently than task 3 by all subjects.

Task 4: Zig-zag movements

As stated in the introduction, the zig-zag pattern of task 4 had to be performed in order to be able to infer whether LI subjects use wrist or finger movements for the production of upstrokes. On the basis of findings of

Teulings et al. (in press) we should find a high writing speed in strokes performed by wrist movements and a low writing speed in strokes performed by finger movements. LI writers should therefore produce faster downstrokes faster than upstrokes.

Task 5 and 6: Wide writing movements

Using right-handed subjects Maarse and Thomassen (1983) found that changing the horizontal spacing of cursive handwriting mainly affected the kinematics of connecting upstrokes. In the tasks 5 and 6 of the present experiment RN, LN and LI subjects had to write the word *duur* in a *normal* and in a *wider* horizontal spacing condition. If horizontal displacements of the writing hand during the writing of a word are more difficult to realize for left-handed than for right-handed subjects, the *wider* horizontal spacing condition in task 6 should affect the movement kinematics of left-handed subjects more than that of right-handed subjects.

Tasks 7 to 12: Left-to-right progression movements

During the cursive production of long words, one can usually observe one or more pen lifts. During these pen-lifts the writing hand is moved slightly to the right. With the tasks 7 to 12 we wanted to explore variations in the number of pen-lift movements and the distance covered during these pen-lift movements as a function of writing hand and hand posture. We expected that these differences would become more apparent when subjects had to write words of increasing length and complexity. In task 7, 8 and 9 the Dutch words *lel*, *lellen* and *lellebel* had to be written. These words consisted mainly of counterclockwise rotating movements and were therefore considered easier than the Dutch words *maan*, *maandag* and *maandagen* in tasks 10, 11 and 12, respectively. In the latter three tasks changes in rotation direction had to be realized throughout the words. We expected that with increasing word length and with increasing demands on rotational directions of writing the number and distance of pen-lift movements would increase.

Procedure and apparatus

After classifying the subject's handedness and hand posture he/she was seated at a table on which was placed, parallel to the table's edges, a digitizer (Calcomp 9240) with a spatial error of 0.2 mm. The writing tasks had to be performed with a ballpoint pen which was slightly thicker than normal and connected through a thin wire with a PDP-11/45 computer. Following some general instructions about the experiment, a lined writing paper (A4) was handed out. This paper had to be placed on the digitizer in the way he or she would normally do that in his or her daily writing activities. After the subject

wrote his/her name on the paper, the experimenter recorded the angle under which the sheet was oriented relative to the writing table. Then a non-lineated paper (format A4) was taped onto the digitizer in exactly the same way as the subject had placed the lineated sheet. Each task was performed eight times, twice in each of the four corners of the A4 sheet. Four black dots in the corners of this paper indicated the different positions at which the writing tasks had to be performed. These dots were black enough to be seen through a writing sheet placed on top of it.

For each of the twelve writing tasks a new sheet of writing paper was used. This paper had to be placed on top of the one taped to the digitizer. The twelve writing tasks were performed in the same order for each subject. This order corresponds to the one depicted in Fig. 1. Each task was performed in blocks of eight successive replications. The first replication had to be performed at the *upper-left*, the second at the *upper-right*, the third at the *lower-left* and the fourth at the *lower-right* corner of the writing paper. The second four replications had to be performed in the same order as the first four, now on the back of the paper. The different positions on the writing paper where the tasks had to be performed enabled us to verify by means of observation whether the subjects continued to use their hand posture during the experiment or not. We also argued that minor postural adjustments as a result of having to write at the prescribed writing areas guaranteed an ecologically valid writing situation. When the pen was positioned at the correct location at the beginning of a trial the subject was shown a written example of the writing task to be performed. Then a low tone indicated that the subject could start writing. A 6 s sampling period followed during which the XY position of the penpoint and the axial pen pressure were recorded with a sampling rate of 105 Hz. If in the 6 s sampling period the penpoint was slightly lifted off the writing paper (i.e., no more than 2 cm above the XY tablet) the XY position was still recorded with a sampling rate of 105 Hz. This enabled us to investigate the penpoint trajectories during pen-lift movements. The end of a trial was indicated by a high tone after which the subject had to move to the position at which the next trial had to be performed. Subjects were asked to write fast, accurately and legibly in their own writing style and to follow these instructions throughout the experiment.

Data analysis

Data analyses were performed on a VAX-11/750 computer. Each recorded signal was first digitally filtered with a high cut-off frequency of 12 Hz. Of each record the absolute (tangential) velocity pattern was derived and displayed (see Fig. 1). By means of an interactive computer analysis program a specific number of upstrokes and downstrokes per task were

selected. A stroke was defined by two successive minima in the absolute velocity function. In tasks 1 to 4, five successive up-downstroke combinations were selected, the first stroke always being the second upstroke. In tasks 5 and 6, four successive up-downstroke combinations were selected, together representing the two letters *uu* of the the word *duur*. In tasks 7 to 9 the first three up-downstroke combinations were selected forming the letters *lel* of the words *lel*, *lellen* and *lellebel*. Finally in the last three tasks, seven up-downstroke combinations were selected, representing the letters *maa* from the words *maan*, *maandag* and *maandagen*.

Of each selected stroke the following measures were calculated: movement time (MT), distance (D), mean velocity (V), maximum velocity (VMAX), mean axial pen-point pressure (P), dysfluency (DYS) and the angle of the stroke relative to the digitizer. The dysfluency of a stroke was measured by calculating the number of absolute velocity inversions per second which was earlier shown to be an appropriate measure of dysfluency (see Meulenbroek & Van Galen 1988). Further data analysis consisted of analyses of variance with appropriate MANOVA repeated measures designs. Group (with three levels: RN, LI and LN) and Gender were the between-subject variables and Rotation direction, Stroke stype (up versus downstrokes) and Word length were the within-subject variables dependent upon the task analyzed. The number and distance of pen-lift movements during word production and the total width of the selected trajectories were analyzed separately.

RESULTS

The results will be discussed in the following order. First the overall effects of writing hand, hand posture and gender on the kinematic handwriting performance measures will be described followed by a description of the orientation of upstrokes and downstrokes of RN, LI and LN subjects. Separate descriptions of the results of the successive tasks follow, in correspondence with the description of the tasks given above.

Kinematic variations as a function of subject variables

Variations in handwriting performance as a function of handedness, hand posture and gender are depicted in Fig. 2. Task 6 was excluded from this analysis because in this task subjects had to write *wider* which affected their normal way of writing. In the other tasks no such instruction was given and normal handwriting was required. The analysis showed that only a few variations reached significance. Left-handed male subjects with an inverted hand posture tended to write relatively small as compared to the other subject

groups. Mean and maximum velocities showed no significant variations as a result of the between-subject variables, although male subjects tended to write faster than female subjects. Axial pen pressure of male writing was significantly higher than of female writing (respectively, 170 and 125 grams; $(F(1,21)=7.38; p<.05)$). LN subjects wrote more fluently than LI subjects $(F(1,21)=4.87; p<.05)$ and females wrote more fluently than males in the LI group whereas the reverse was true in the LN group $(F(1,21)=3.05; p<.10)$.

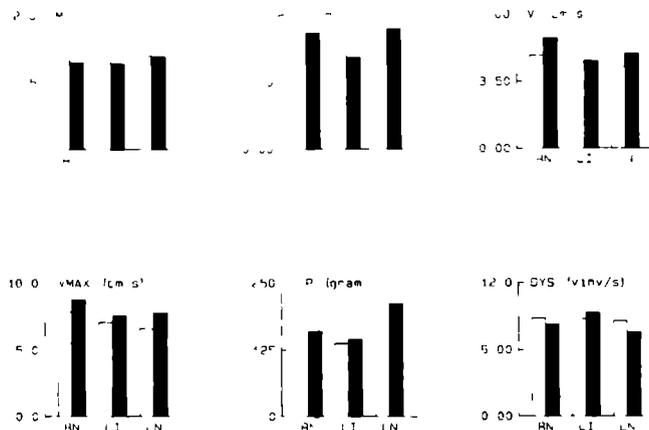


Figure 2. Mean movement time (MT), distance (D), velocity (V), maximum velocity (VMAX), penpoint pressure (P) and dysfluency (DYS) of cursive handwriting strokes as a function of writing hand and hand posture (RN: right-handed, normal hand posture; LI: left-handed, inverted hand posture and LN: left-handed and normal hand posture) and gender (female: white bars; male: black bars).

Orientation of upstrokes and downstrokes

Fig. 3 shows six polar frequency distributions of stroke directions relative to the writing paper (upper row) and relative to the digitizer (lower row) for the RN group (left column; $n = 7,923$), LI group (middle column; $n = 7,716$) and LN group (right column; $n = 5,344$), separately. Task 6 was excluded from this analysis for the reasons mentioned above. Observations during the experiment showed that subjects continued to use their categorized hand posture throughout the experiment. On average, RN and LI subjects rotated their writing paper counterclockwise, 20 and 7 degrees, respectively. LN subjects rotated their writing paper 16 degrees clockwise. As can be seen from the top row of graphs in Fig. 3, the orientation of strokes relative to the writing paper was consistent for the RN, LI and LN group. The upstrokes were oriented on the paper in an angle of 40 degrees for all groups

($F(2,24)=0.51$; $p>.10$). Downstrokes were oriented on the writing paper in angles of 246, 243 and 253 degrees for the RN, LI and LN group, respectively, ($F(2,24)=2.57$; $p>.05$). A different picture appears when we look at the orientation of strokes relative to the digitizer. Upstrokes were produced with a mean angle of 58, 48 and 34 degrees by RN, LI and LN subjects, respectively. Standard deviations were large and there were, typically, several lobes in the upstroke distributions. However, these differences appeared not to be significant ($F(2,24)=1.06$; $p>.10$). With regard to the downstrokes a significant Group effect was present ($F(2,24)=6.10$; $p<.01$). RN subjects produced downstrokes with a mean angle of 265 degrees whereas downstrokes produced by LI and LN subjects were less vertically oriented (250 and 237 degrees, respectively). Fig. 3 shows, furthermore, that a non-inverted hand posture leads to more variation in stroke directions between subjects than the inverted hand posture. The polar plot of the LI subjects, relative to the digitizer, indicates that the inverted hand posture results in very consistently oriented downstrokes approximating an angle of 250 degrees. It is likely that the inverted hand position allows subjects to make movements only in a few directions.

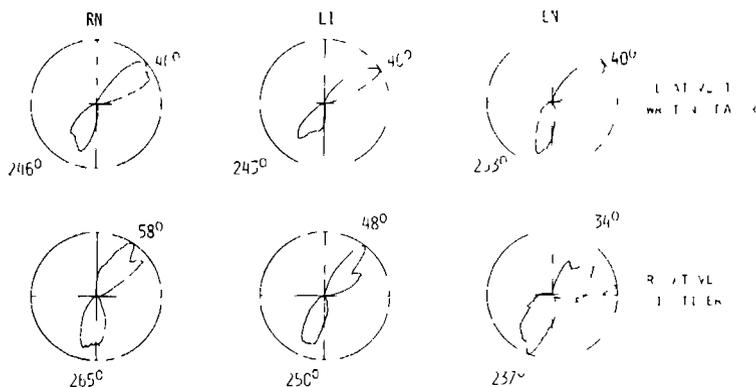


Figure 3. Polar distributions of realized stroke directions, relative to the writing paper (upper graphs) and relative to the digitizer (lower graphs), for the three experimental groups (RN: 7,923 strokes produced by righthanders with a normal posture; LI: 7,716 strokes produced by lefthanders with an inverted hand posture and LN: 5,344 strokes produced by lefthanders with a normal hand posture).

Task 1: Ellipses

Nine of the ten right-handed subjects wrote the ellipses in task 1 with

counterclockwise rotating movements. Three out of ten LI and two out of seven LN subjects performed clockwise movements in task 1. That these latter numbers were not bigger is probably due to the fact that the subjects did not conceive this task as a *drawing task* since the experiment was presented to them as a study on cursive handwriting performance. The main objective of task 1 was to investigate Group and Gender differences in movement kinematics in a task which demanded no progression movements. However, besides a significant main effect of Gender on pen pressure (138 grams in female and 169 grams in male subjects; $F(1,21)=4.71$; $p<.05$) no effects of Group and Gender on performance measures were found. Stroke Type (up versus downstrokes) only influenced the maximum velocity, in upstrokes amounting to 15.0 cm/s and in downstrokes to 14.4 cm/s ($F(1,21)=4.84$; $p<.05$).

Task 2 and 3: Rotating writing movements

The objective of tasks 2 and 3 was to test the hypothesis that counterclockwise movements are written faster than clockwise movements regardless handedness and hand posture. This because the former type of movements are dominant in cursive script.

Besides the main effect of Gender on pen pressure, no main effects of Group and Gender were found. As predicted, mean writing velocity of counterclockwise rotating movements in task two was higher than of clockwise rotating movements in task three (6.228 and 5.363 cm/s, respectively, ($F(1,21)=12.07$; $p<.01$). The effect of Stroke Type (up versus downstrokes) on maximum velocity was identical to the one found in task 1. An additional effect of Stroke Type was found on movement distance. Upstrokes were 1.47 cm on average and downstrokes only 0.94 cm ($F(1,21)=84.93$; $p<.01$), showing that when a left-to-right progression is superimposed upon continuously rotating movements, upstrokes are relatively lengthened and downstrokes shortened. No interactions between Group, Gender and within-subject variables relevant to the hypothesis under investigation were found. A significant interaction of Rotation Direction and Stroke Type was found on pen pressure indicating that upstrokes contained higher pressure than downstrokes in task 2 (137 versus 133 grams, respectively) whereas the reverse was the case in task 3 (142 versus 147 grams; $F(1,21)=12.32$; $p<.01$).

Task 4: Zig-zag movements

We expected that that the upstrokes of the zig-zag pattern would be performed more efficiently than the downstrokes, at least in righthanders (Meulenbroek & Van Galen 1986). The reverse should be found for the LI

group according to Wing's suggestions (1978). Upstrokes were 0.337 cm longer than downstrokes ($F(1,21)=119.89$; $p<.01$) and were produced with higher mean and maximum velocities (respectively, $F(1,21)=25.52$; $p<.01$; $F(1,21)=40.28$; $p<.01$). These findings correspond with those of Meulenbroek and Van Galen (1986). Fig. 4 shows the effects of handedness and hand posture on mean and maximum velocity of upstrokes and downstrokes in task 4. Because the individual differences within the RN, LI and LN groups are large, no significant main effects of Group on mean and maximum velocity were present. The interactions between Group and Stroke Type on mean velocity and maximum velocity appeared to be significant ($F(2,21)=5.84$; $p<.05$ and $F(2,21)=4.93$; $p<.05$, respectively). The difference in mean and maximum velocity between upstrokes and downstrokes is larger in the RN group than in the LI and LN groups. However, the data do not confirm the predictions derived from Wing's (1978) suggestions. The downstrokes of the LI subjects were not produced with higher velocities as would have been expected when these downstrokes are performed by wrist movements.

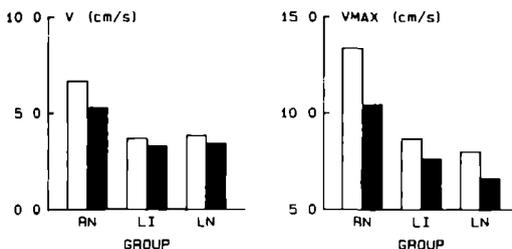


Figure 4. Mean velocity (V) and maximum velocity (VMAX) of upstrokes (white bars) and downstrokes (black bars) produced in the zigzag pattern of task 4 by RN, LI and LN subjects.

Task 5 and 6: Wide writing movements

We expected that if left-to-right progression movements are more difficult to realize for left-handed than for right-handed subjects the *wider* horizontal spacing condition in task 6 would affect the writing performance of lefthanders more than the writing performance of righthanders.

A control analysis on the width of writing showed that the letters *uu* were 0.534 cm wide in task 5, and 0.876 cm wide in task 6 ($F(1,21)=96.11$; $p<.01$). On average, RN, LI and LN subjects wrote these two letters within horizontal distances of 0.641 cm, 0.705 cm and 0.744 cm, respectively. These differences were not significant, however. The analysis showed furthermore that the horizontal spacing condition equally affected the writing

width of the RN, LI and LN subjects. No significant interactions between the subject and task variables were found in the other kinematic performance measures which shows that any differences between lefthanders and righthanders in the production of left-to-right progression movements are not detectable in words of only four letters, even if these words have to be written wider.

Tasks 7 to 12: Left-to-right progression movements

Fig. 5 shows that word length differentially affected the number of words containing at least one pen-lift trajectory as well as the mean movement distance of these pen-lift trajectories. The leftmost panel of Fig. 5 shows that lefthanders used more often pen-lift movements than righthanders and that the number of words containing at least one pen-lift movement increased more strongly with increasing word length for non-inverters than for inverters. The central panel of Fig. 5 shows that with increasing word length LN subjects increased their distance of pen-lift movements more strongly than LI subjects. Furthermore, LI subjects covered a greater distance during pen-lift movements than RN subjects ($F(4,6)=4.56$; $p<.05$). These results could not be attributed to the effect of word length on the width of writing as can be seen in the rightmost panel of Fig. 5. Although the realized mean word width of *lel* and *maa* in the last six tasks decreased with increasing wordlength ($F(1,21)=429.44$; $p<.01$), this effect did not interact with the Group factor. Furthermore, the analysis showed that the number and distance of pen-lift movements did not vary as a function of changes in rotational directions in the words of tasks 10 to 12 as compared to the words of tasks 7 to 9 in which no changes of rotational direction occurred. The non-inverted hand posture used by a minority of lefthanders, mainly female writers, seemingly elicits more and longer pen-lift movement trajectories than the inverted hand posture when writing tasks become more complex. If we consider a low number and short distances of pen-lift movements as an indication of writing efficiency the results indicate that the inverted hand posture, in that sense, is more efficient than the non-inverted hand posture.

DISCUSSION

The results of this experiment show that variations in cursive handwriting performance as a function of handedness, hand posture and gender can mainly be found in the orientation of upstrokes and downstrokes and in the number of pen-lift movements used during the production of long words. The results do not confirm Wing's (1978) hypothesis that left-handed inverters use wrist movements for the production of downstrokes. Herron (1980),

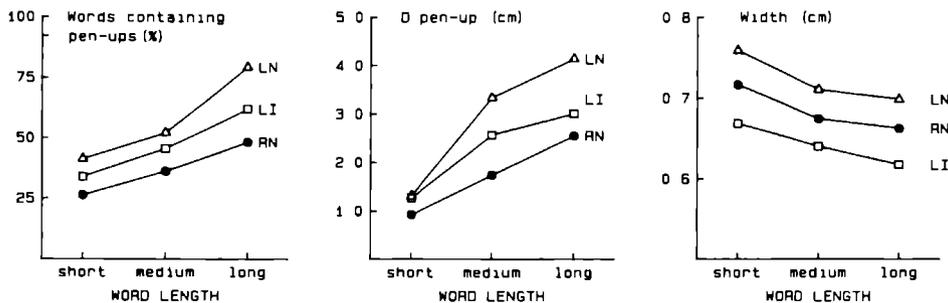


Figure 5. Left-most panel: number of words containing pen-ups indicated as a percentage of the total number of short words (task 7 and 10), medium words (task 8 and 11) and long words (task 9 and 12) for RN, LI and LN subjects. Central panel: mean writing distance of pen-lift movements during the production of short, medium long and long words by RN, LI and LN subjects. Mean writing width of *lel* and *maa* in short, medium and long words for RN, LI and LN subjects.

however, thought the movements of the wrist responsible for diagonal upstrokes in left-inverters. She argued that lefthanders invert their hand position in order to be able to use wrist movements in the same way as righthanders do. The present results confirm Herron's (1980) suggestion, that left-handed inverters produce upstrokes by means of wrist movements in the same way as right-handed writers do because the former subjects also produced faster upstrokes than downstrokes in a zig-zag pattern.

The spatial differences between righthanded and lefthanded strokes did not affect the writing product since lefthanders were able to produce a cursive script which, on the writing paper, was slanted to the right in the same way as the right-slanted cursive script of righthanders. The spatial analysis of upstrokes and downstrokes relative to the digitizer indicated that left-handed inverters choose a strategic writing posture which enables them to *lock* the anatomical subsystem of the writing hand. This might be a solution for the degrees of freedom problem which they would encounter if they write with the left hand in a non-inverted position. By choosing the inverted writing posture lefthanders are able to produce very consistently oriented upstrokes and slightly less slanted, but also very consistently oriented, downstrokes. This writing strategy also results in writing which is less wide than that of non-inverted lefthanders. Non-inverted lefthanders, trying to produce cursive script which is also slanted to the right, have to cope with a situation in which the subsystems of hand and fingers have to cooperate in a complex fashion because the spontaneous movements of the hand around the wrist joint is perpendicular to the line of writing. Although they appropriately

rotate the writing paper on the table 16 degrees clockwise their upstrokes are inconsistently oriented in space. Left-to-right progression movements are realized by lifting the pen off the paper and relocating the hand on the writing paper but also by decreasing the slant of upstrokes (Maarse & Thomassen 1983). The typical *lobes* in the upstroke distribution of the polar plots in Fig. 5 probably reflect the between-subject variance of this progression strategy. Having to push the left hand into the left-to-right direction in which our cursive script is produced, non-inverted lefthanders lift the pen more often and along longer trajectories than inverted lefthanders and righthanders. The result of this strategy is a wider writing product than that of inverted lefthanders and that of righthanders.

The kinematic analyses of the digitally recorded handwriting movements indicated that hardly any differences appear to be present in the efficiency with which RN, LN and LI subjects produce handwriting strokes. Only very small differences in writing speed and dysfluency between the subject groups were found. Male subjects tended to perform the writing tasks in this experiment in a way somewhat different than female subjects. Male subjects wrote smaller, faster and with more pen pressure than female subjects. The results showed, furthermore, that effects of increasing task complexity on kinematic performance measures did not interact with writing hand, hand posture and gender. The effects as such confirmed different earlier findings regarding the complexity of rotation direction and the motoric differences between up and downstrokes.

Given the findings that inverted lefthanders produced very consistently oriented handwriting strokes and used little and short pen-lift movements during word production, the conclusion seems to be warranted that the inverted hand position is a relative efficient solution for the problem of writing with the left hand. The inverted hand position used by most lefthanders may be considered more as a functional adaptation to the necessity of writing from left to right, as Enström (1966), Wahl (1955) and Herron (1980) suggested, than a consequence of neuroanatomical asymmetry, as Levy and Reid (1978) and Geschwind and Galaburda (1985) suggested. Levy and Reid (1978) claimed that a non-inverted hand posture indicates right-hemispheric speech lateralization whereas an inverted hand posture indicates left-hemispheric speech lateralization. The relation between handedness, hand posture and cerebral organization has subsequently been investigated and discussed extensively by Weber and Bradshaw (1981), Levy (1982) and Geschwind and Galaburda (1985) and is still a matter of debate. Levy (1982) suggested that experiments describing in detail the motoric differences

between right-handed subjects and inverted and non-inverted left-handed subjects should improve our understanding of the differences between these groups, which is a necessary requirement to understand the relation between brain organization, writing hand and hand posture. The present study contributed indirectly to this issue by trying to determine to what degree the inverted hand position, used by most lefthanders, can be considered as a functional adaption to the global and specific movement directions at the level of words and strokes in our script.

A final conclusion with regard to educational practices which may be made from the present empirical findings concerns the initial training of specific hand postures in lefthanders. If Enstrøm's (1962) suggestion is correct, i.e., that the non-inverted hand posture is most suited for the initial phases of formal handwriting education, the results of the present experiment at least suggest that a transition of the non-inverted to the inverted hand posture during a specific training period might be considered if prevailing writing problems occur with a non-inverted left-handed writer.

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Chapter 7

Epilogue

APPLICATIONS OF HANDWRITING RESEARCH TO THE ORGANIZATION AND CONTENTS OF HANDWRITING CURRICULA

Introduction

This epilogue is concerned with applications of three different aspects of handwriting research to the organization and contents of handwriting curricula. These aspects are (1) theoretical notions regarding the psychomotoric processes underlying the production of handwriting movements, (2) empirical data concerning the production of handwriting movements collected in the experiments of this thesis, and (3) technological developments of handwriting-analysis techniques which enable both the researcher and the educator to record and evaluate handwriting movements with a high degree of precision. We will start by providing a global description of present-day handwriting education in the Netherlands. At several points in the present chapter we will describe certain Dutch training practices more precisely. These descriptions are based on a close examination of twelve Dutch handwriting curricula (Meulenbroek & De Klerk 1985), on information obtained during seminars and discussions with educationalists, and on classroom observations made in one of the primary schools which participated in several of the experiments reported in this thesis. Although the descriptions are brief and schematic, they enable us to identify possible loci of improvement in the existing handwriting curricula as a result of future applications of handwriting research. This chapter is a condensed compilation of three publications. The first article (Meulenbroek & Van Galen 1988) discusses principles of curriculum development on the basis of theoretical and empirical aspects of handwriting research. The second publication (Hylkema, Meulenbroek & Van Galen 1988) consists of a technical report of the Nijmegen Institute of Cognition research and Information technology presenting a conception of a handwriting curriculum based on this thesis. The third publication (Meulenbroek 1989) indicates some possible applications of computer-assisted recording and analysis techniques concerning handwriting movements in the field of remedial teaching. The aim of this chapter is to elicit a fruitful discussion between educationalists developing and employing handwriting curricula and investigators conducting handwriting research.

Global organization of current handwriting curricula in the Netherlands

Recently, nursery and primary schools in the Netherlands have been combined, so that at present children receive eight years of primary

education after entering school at the age of four. The general aim of the handwriting curricula used in primary school is to assist the children in the development of a reasonably fast, legible and personal style of handwriting. Preparatory, primary and advanced stages of training can be distinguished. Handwriting education starts with some general preparatory activities during the first two years. These involve the global training of perceptual-motor skills, attending to the developing efficiency of the hands of each child and familiarizing the children with writing materials by means of drawing tasks. In the third year, primary handwriting education starts with the practice of simple stroke sequences, i.e., repetitive connected writing patterns. These patterns are trained regularly during about three months. Simultaneously, the children start with a reading program and, consequently, are made familiar with printed letter forms. These letter forms are often also trained motorically in handwriting tasks. To the extent that such a practice is adhered to, children are thus also trained in a *manuscript* (i.e., print) style of handwriting. After three months of practising simple stroke sequences and learning to read (and write) manuscript letter forms, single cursive letter forms are introduced. Once having learned how to write a small number of cursive letters, small words are practised. At the end of the third year of handwriting education, capitals, numbers and punctuation marks are being mastered. Advanced handwriting may be regarded to commence in the fifth year, i.e., at the age of eight. Exercises now consist of the writing of increasingly larger pieces of text, of writing faster and of practising several styles of writing in order to elicit a personal style of writing. The regularity of handwriting (e.g., the constancy in letter formation, word- and letter spacing, writing size and slant) and the overall legibility of the products are the main observational criteria used by teachers to evaluate the effects of education.

Psychomotoric components involved in the production of handwriting

In order to indicate certain possible changes of handwriting curricula on the basis of theoretical aspects of handwriting research, an account of some essential psychomotoric components and processes involved in the production of handwriting movements will now be given. The mixed linear and parallel model of the production of handwriting movements (Van Galen, Meulenbroek & Hylkema 1986; Van Galen, Smyth, Meulenbroek & Hylkema, in press), discussed in chapter 1 of this thesis, distinguishes six different information-processing levels at which representations of various handwriting units are processed. With regard to these units, words, letters and strokes can be distinguished. The retrieval of the orthography, or the spelling of a word, resulting in (1) a sequence of graphemes (letters), is followed by the determination of (2) a sequence of allographs. An allograph

is defined as one of the possible forms of a grapheme (e.g., upper or lower case). The sequence of allographs determines the retrieval of (3) specific motor programs from motor memory. These programs most likely contain abstract spatial information on the letter forms (Teulings 1988). The motor programs are subsequently processed with regard to (5) movement parameters like size and speed and, finally, the individual strokes are prepared by the activation of (6) the proper motor units in the motor system. While these processes on the representations of a word, its letters and strokes, occur in a hierarchical manner, the subject is able to process different units simultaneously. The subject is ahead in time with regard to the preparation of subsequent handwriting units: the larger units at the higher levels in the hierarchy are processed earlier than the smaller units at the lowest levels. An experienced writer performs a stroke in about a tenth of a second. Once a stroke is initiated, the writer cannot alter the movement direction until the penpoint has reached the end of the stroke, i.e., strokes are presumably executed in a ballistic mode.

The model described above consists of a hierarchy of psychomotoric components essential to the production of skilled handwriting movements. The components of the hierarchy might be considered as subroutines, or subskills, underlying the handwriting skill. Following Kay (1970) and Bruner (1970), we assume that the acquisition of a skill can be characterized by the gradual incorporation of the subskills of the skill into an overall action program. Eventually, the subject will be able to coordinate the subskills efficiently by means of this action program. The overall result will be a skilled performance which, at a behavioral level, seems to run off automatically. In chapter 1 we argued that children will learn the subroutines of the handwriting skill in an order which is roughly the inverse of the order of the processes described by the model. The more peripheral subroutines will be learned before the central ones are mastered. In fact, the central subroutines build up on the peripheral ones. The linear aspect of the model therefore implies a specific order of subskills to be trained in a handwriting curriculum. As far as the handwriting units are concerned, this order should be reflected in a curriculum by a sequence of exercises which successively train the production of strokes, letters, and words. Before indicating several possible training techniques aiming at the skilled processing of the internal representations of these handwriting units, we will discuss some general implications of the parallel aspects of the model.

An important characteristic of the model concerns the presumably concurrent, or parallel, manner in which information is processed. The model states that during the execution of a specific stroke, the subject simultaneously specifies the movement parameters of a subsequent stroke,

retrieves the motor program of a subsequent allograph, selects the allograph of a subsequent grapheme and determines the grapheme sequence of a subsequent word. This aspect of concurrency is based on detailed observations of the dynamic characteristics of adult handwriting (Van Galen et al. 1986; Van Galen et al., in press) which have shown that (1) adult handwriting consists of regular patterns of bursts of energy in agonist and antagonist muscle groups resulting in ballistically produced upstrokes and downstrokes (see also chapter 3) and, (2) the duration of the intervals in which the strokes are produced varies as a function of the complexity of the information processes at higher levels. It seems therefore plausible that a subject has the ability to process information during movement execution because of the fact that the handwriting movements are executed in a ballistic fashion. When a writer performs writing movements in a non-ballistic, i.e., a closed-loop, manner, he or she is continuously monitoring movement execution on the basis of kinaesthetic, tactile and visual feedback. We assume that these monitoring activities during movement execution reduce the subject's ability to prepare subsequent handwriting units adequately.

An implication of the notion of concurrent processing for the development of handwriting curricula concerns the choice of an instructional technique for teaching children the subskills of handwriting. A suitable technique should elicit movements which can be performed reasonably fast and in a ballistic manner. Traditionally, handwriting curricula have relied on tracing and copying techniques to teach children the handwriting skill (Askov, Otto & Askov 1970; Barbe, Lucas & Wasylyk 1984). Except for the study of Birch & Lefford (1967), most studies comparing the effectiveness of tracing and copying (e.g., Hirsch & Niedermeyer 1973; Askov & Greff 1975; Sjøvik 1976) showed that tracing is a less effective technique to practise handwriting than copying is. Tracing a pre-printed letter form, asks for the continuous comparison of the trace of ink flowing from the pen-point on the writing surface, with the pre-printed letter form. Copying a letter, however, elicits a different movement strategy. First, the letter has to be perceived and analyzed. Subsequently, a movement plan has to be constructed. Finally, this plan is instantiated to control movement execution. Furthermore, having to copy a sequence of relatively small handwriting units will probably elicit the preparation of the production of subsequent units during actual movement execution. The amount of *overlap*, of course, depends on the overall size of the units and on the rate at which the sequence is copied. In copying, the visual evaluation of the (small) units as a written product generally occurs only after the copying attempt has finished. In our view, handwriting curricula should indeed provide exercises which elicit an adequate preparation of the handwriting task. Such a preparation is not only a

necessary requirement for, but will probably also lead to, the fluent and uninterrupted production of strokes and letters.

Having discussed the two most important aspects of the mixed linear and parallel model of the production of handwriting movements, viz., the hierarchy of information-processing levels and the concurrent manner in which the information at the various levels within the hierarchy is being processed, we will now describe the contents of a possible handwriting curriculum more specifically.

In our view, a curriculum should start with exercises which first practise the selection of muscle groups relevant to the performance of handwriting movements. These exercises may consist of simple patterns which elicit the execution of singular arm, hand and finger movements in the two-dimensional, horizontal plane, without any constraints on size or accuracy. By experiencing the sensory consequences of the activation of the muscle groups resulting in such arm, hand and finger movements, the child learns the relationship between the selection and initiation of these muscle groups and the resulting movement direction. In addition to five or six years of having experienced this relationship in spontaneous motor behavior, the child will have to learn to generalize these experiences to graphic motor behavior and, moreover, to master the relationship between specific muscle activities and the resulting drawing or writing traces. Subsequently, exercises should be provided which give the child the opportunity to experience the relationship between variations in muscle force and the corresponding variations in movement speed. These exercises might consist of patterns eliciting individual movements of arm, hand or fingers in the horizontal plane in varying sizes. These exercises will teach the child the direct relationship between variations in muscle force and variations in movement size, which is a highly characteristic aspect of handwriting production (Denier Van Der Gon & Thuring 1965). Thirdly, the curriculum should provide exercises which train the child to initiate a sequence of muscle innervations. These latter exercises might consist of drawings which elicit planning activities concerning the performance of two or more submovements, i.e., combinations of arm, hand and finger movements, each submovement having its own direction and size.

After practising the initiation of muscle groups, the parameterization of movement parameters and the planning of stroke combinations, the cursive allographs can be introduced. The model assumes that relatively stable representations of cursive allographs will be retained in motor memory in the form of motor programs. Since these programs probably contain spatial information concerning stroke directions, an instructional technique which emphasizes stroke directions may be recommended. Because of our emphasis

on preparational activities before actual performance, the technique of copying might be extended with explicit instructions to decompose a new letter into a stroke sequence and to analyze the directions of the separate strokes before the first writing attempt is undertaken. This suggestion corresponds to the recent emphasis on cognitive preparational activities in motor learning (cf. Heuer 1985; Shea & Zimny 1988). Earlier, the Russian educationalist Pantina (1957) provided empirical evidence that such a preparational technique, i.e., one in which the pupils search for those points in the letter where the movement direction changes, appeared to yield optimal learning results. This technique has become known since as an *orientation* technique in learning the skill of handwriting. However, in contrast with the instruction technique of Pantina, which elicits a preparational strategy at the level of letters, our approach emphasizes preparational activities at the other levels of the information-processing system as well. At this point in the curriculum these levels concern the programming, the parameterization and the initiation of handwriting movements leading to the graphic production of allographs.

In this stage of handwriting education, the curriculum should provide a training technique to teach the children to write most of the 26 allographs of our cursive alphabet. According to the model, the children have to build up stable internal representations of these cursive allographs, i.e., motor programs. In order to increase the strength of the motor programs in motor memory, we assume that the cursive allographs will have to be trained a considerable number of times. The size of the motoric realisations, however, will not be stored within these programs. Consequently, instructions with regard to movement size might vary while the child is producing his or her first number of attempts in writing a new cursive allograph (Teulings & Thomassen 1985). By having to change the writing size, the child keeps practising the relationship between muscle force and movement size. After thus having practised writing a few cursive allographs, connected allograph pairs might be trained. This component of the curriculum practises two aspects of the handwriting production process simultaneously. By instructing the child to perform an efficient connecting trajectory between two allographs on the basis of attending to (1) the positions of the penpoint at the end of one allograph and at the beginning of the subsequent allograph and, (2) the rotational directions of the exit stroke of one allograph and the entry stroke of the subsequent allograph, the subskill of producing letter connections is being practised (see chapter 5). At the same time, the retrieval of motor programs from motor memory is trained because the performance of the second letter has to be prepared in time. When letter pairs have to be produced under speed instructions, the retrieval of the representation of the

second letter will have to be achieved in advance, or at least during the performance of the first letter of the letter pair.

Up to this point in the curriculum, the writing tasks will generally have been presented visually, i.e., the graphic information that guides the training activities of the child, is pre-printed in the exercise books. However, a different mode of presenting information which is hardly ever used in current handwriting curricula may be considered, i.e., the presentation of acoustic information. The production of individual allographs and allograph combinations might be trained by presenting the child the corresponding phonemes and diphones. This type of presentation elicits more preparational activities than the mere copying of preprinted material, e.g., it guarantees that the retrieval of memory representations is being practised. The latter, of course, also holds when the child is presented *printed* letter forms and forced to produce cursive allographs (see chapter 4). The acoustic presentation mode might also be used at later stages in the handwriting curriculum, viz., when children practise the production of new allographic forms of a grapheme (e.g., the upper-case letter forms), words and phrases. These latter aspects of the production process might be trained in dictation tasks in which the children have to process words, derive grapheme sequences, select allographs and prepare the motoric processes of handwriting performance on the basis of acoustically perceived information.

Having described the components, the order of components, and some instructional techniques of a possible handwriting curriculum on the basis of the theoretical notions concerning the psychomotoric components underlying handwriting performance, a few comments with regard to the limitations of these implications must be made. The educational value of the model is restricted in the sense that important variables like motivation, IQ-differences and individual learning styles are not considered. These variables have a strong influence on the learning processes evolving as a result of the interactions between the child, the curriculum and the teacher. Nevertheless, we regard the skill approach as a valuable approach to analyze the essential subskills of handwriting. The suggestions for handwriting curricula presented in the previous paragraphs need to be discussed further with educationalists. They will also have to be tested as to their effectiveness in applied, future research. Besides our theoretical notions of handwriting, the empirical data collected in the series of experiments reported in this thesis may also be discussed with regard to their implications for the development of handwriting curricula. We will now discuss some implications of the experimental results successively described in the chapters 2 to 6 of this thesis.

Implications of the present research for the development of handwriting curricula

The production of line drawings

Chapter 2 reports an experiment concerning the preparation of one and two-element line drawings, small and large line drawings and line drawings performed by wrist or by finger movements. The experimental results confirm the independence of the aspects of motor programming, parameterization and initiation of handwriting movements. These aspects form a central part of the mixed linear and parallel model of the production of handwriting movements, according to which they are assigned to successive, independent processing stages. The general implications of this model for handwriting education have been discussed in the previous paragraphs. The task used in the first experiment may also have some consequences for handwriting education. A choice-reaction task, performed under speed instructions, requires a subject to respond quickly to a visual stimulus containing information about the intended response. After perceiving and recognizing the stimulus, the subject has to select the proper motor program, to set the proper movement parameters, and to prepare the proper muscle groups to initiate the required movements. Reaction time reflects the speed at which a subject is able to perform these basic psychomotoric preparations of the movements. At present, it seems to us that such an experimental situation cannot be used in handwriting education, but an alternative may be considered. Writing exercises which demand the successive preparation of different handwriting units probably provide a training in psychomotoric preparational activities more than writing exercises in which children repeatedly have to perform the same handwriting units. Furthermore, and probably more importantly, instructing children to prepare the production of handwriting units before they begin to write may increase the strength of the entire motor program and it reduces the chance of having to interrupt the execution as a result of inadequate or incomplete preparation.

The production of stroke sequences

Chapter 3 reports an experiment with primary-school children performing simple stroke sequences in various speed, accuracy and size conditions. The results show that the quality of the stroke-production process is higher with continuous writing patterns (i.e., patterns in which the movement direction changes gradually) than with discontinuous (i.e., patterns containing sharp corners). Except for the wave pattern, the continuous patterns were also performed faster than the discontinuous ones. However, within the set of discontinuous patterns, strokes ending in a sharp corner were performed

more fluently than strokes ending in a gradually changing curve. It was argued that in writing discontinuous patterns the child probably prepares a subsequent stroke during the stop of the pen at a sharp corner of the writing pattern. In other words, discontinuous patterns elicit an alternation of preparation and execution, whereas continuous patterns probably ask for concurrent preparation and execution. According to our view, the latter movement-production strategy is more difficult for a child in the preparatory phase of handwriting education than the former. Discontinuous patterns should therefore be practised before continuous patterns. Among the patterns investigated, the wave form appeared to be a very complex pattern to be performed by children. The wave form probably requires the continuous monitoring of ongoing changes in movement direction. Since the wave form is hardly reflected in the allographs or connections of the allographs of our cursive alphabet, this writing pattern might well be excluded from training. Another implication of the experimental results of chapter 3 concerns speed, accuracy and size conditions in producing simple stroke sequences. Speed instructions improve the fluency of the stroke productions, especially when large writing movements have to be made. Writing education should emphasize the relation between the speed and size of writing movements more explicitly than it has been done previously. The combination of accuracy instructions and the presence of lineation at the top of writing patterns must be discouraged because this combination elicits relatively slow writing movements of low quality.

The production of letter forms

The first experiment of chapter 4 investigates factors determining the perceptual-motor complexity of printed and cursive letter forms. It could be shown that presenting a manuscript letter which is normally used in teaching the reading skill, poses the child with a specific problem when he/she has to write the cursive allograph of that grapheme. Primary handwriting education should therefore be careful with the introduction of too many allographic variations of letter forms within a period of only a few months. In order to prevent confusions in selecting allographs it is worthwhile to consider the use of only one allographic variation of the alphabet at the start of primary handwriting education. This means that manuscript letter forms, being taught in the initial phases of reading education, should not be trained as motoric tasks. The memory representations of manuscript allographs built up as a consequence of motoric practice, compete with the memory representations of cursive allographs to be mastered a few months later. Barbe and Johnson (1984) show that one of the major problems in handwriting education in the U.S.A. concerns the change (which is still common practice in US primary

schools) from a manuscript to a cursive writing style after two or three years of practising printed letters. In some recent Dutch handwriting curricula, manuscript letters are visually presented while the cursive allographs of these graphemes have to be written. When determining the order in which children have to learn how to write the allographic letter forms in curricula of this type, educationalists should recognize that some letters are spatially ambiguous, e.g., a manuscript *d* might easily elicit the production of a cursive *b*, and that the production of some cursive letters strongly depends on the presence of context letters, e.g., the manuscript *l* might easily elicit the production of the character **1**, unless it is surrounded by other letters. The frequency with which letters are used in our language is also a factor which must be considered with regard to the order in which children are taught the letter forms of our alphabet. The experimental results also showed that letters containing extenders (i.e., ascenders and descenders) were more easy to write for children than body-sized letters. Letters containing continuously changing movement directions, such as the *r* and *z*, which in Dutch writing curricula often contain horizontal wave-like forms, appeared to be very complex to produce by primary-school children. Cursive letter forms should reflect, as much as possible, a transparent, obvious stroke structure so that the production of ballistic handwriting movements can be achieved. A few other suggestions concerning letter forms are discussed at the end of chapter 4 and in Meulenbroek and De Klerk (1985).

The second experiment of chapter 4 revealed the presence of a discontinuous developmental trend in the kinematic performance measures of handwriting movements of primary-school children. This result has an implication with regard to the evaluation of handwriting performance. It must be recognized that a temporary decline of performance may reflect an important phase in the acquisition of the handwriting skill. Young children appear to be able to produce ballistic movements. They are able to prepare a simple movement properly and to execute the movement without monitoring or interrupting its execution. Eight-year old children, however, frequently disrupt the execution of handwriting movements, probably on the basis of visual feedback. We assume that the visual information is processed during the execution in order to evaluate and, subsequently, to correct the movements. At this stage in the handwriting curriculum, children have already learned how to write the lower-case cursive allographs. However, they probably have not yet developed stable motoric representations of these letter forms. Consequently, these representations are not optimally used for an efficient control of the production process. Until the motoric representations have been properly shaped and can be used to prepare movement sequences, children will monitor their handwriting movements

visually. This may result in a temporary decline in performance.

The production of bigrams

Chapter 5 reports an experiment concerning the production of connecting strokes in cursive bigrams. It was demonstrated that the production of within-letter strokes was based on the retrieval of motor programs from long-term motor memory, whereas the production of connecting strokes was based on a local decision process. When a subject has to connect two letters, he or she has to determine an efficient trajectory between the point at which he or she leaves one letter and enters the next letter. Besides relating these points to the lineation on which the script is produced, the rotation direction of exit and entry movements has to be taken into account. The implication of these findings for handwriting curricula is the recognition that the production of letter forms differs from the production of connecting strokes. Many writing curricula do not explicitly train the production of letter connections. When they do train letter connections separately, they present a fixed number of connection types as if these connection types have to be learned as a specific memory set. Our experimental results imply, however, that it might be a proper technique to teach children the strategy of producing letter connections as a specific subskill in which efficient trajectories have to be prepared in time on the basis of (1) the location of the exit and entry points of letters relative to the local lineation and (2) the rotation direction of exit and entry strokes of letters.

The production of words

Chapter 6 presents an experiment concerning the variations in cursive-handwriting performance as a function of handedness, hand posture and gender. Most lefthanded adults eventually adopt a so-called inverted writing posture. The hand is placed above the line of writing and the penpoint is directed towards the bottom of the page. The non-inverted hand posture in which the subject places the hand beneath the line of writing, seems to be the most efficient for lefthanders in the primary stage of handwriting education (Enstrøm 1966). The results of the experiment, however, showed that, at the levels of stroke and letter production, hardly any significant motoric differences between right-handed, inverted left-handed and non-inverted left-handed adults were present. The differences between the subject groups appeared only at the level of word production. Non-inverted lefthanders lift the pen more often and over longer distances than inverted lefthanders and righthanders. We argued that the inverted hand position is probably an adequate functional adaptation to the global left-to-right direction along which the lines of writing are produced in our culture. We suggest that in

teaching lefthanders the skill of handwriting, special attention should be paid to a change from the non-inverted hand posture to the inverted hand posture whenever persisting writing problems are detected.

Applying current analysis techniques in handwriting education

Up to this point the present chapter has been concerned with implications of theoretical and empirical aspects of handwriting research for the improvement of handwriting curricula. A third source for possible application in handwriting education, as described more extensively in Meulenbroek (1989), is to be found in the use of microcomputers in order to record and analyze handwriting movements very precisely and rapidly. These techniques are currently used mainly in the scientific study of handwriting (see e.g., Thomassen, Keuss & Van Galen 1983; Kao, Van Galen & Hoosain 1986; Plamondon, Suen & Simner, in press). Especially in the field of remedial teaching, in which a one-to-one relationship between teacher and child is normally necessary, a computer-assisted training environment may be of great use. Until now, remedial teachers have to rely mainly on evaluation scales and personal observations in order to diagnose and treat writing problems. Maarse, Thomassen & Teulings (1985) have described the technical requirements, and possible applications, of micro-computers in the field of handwriting education. They explicitly stated that in order to be fruitful these applications require a combined effort of technicians, educationalists and psychologists. The remaining part of this chapter contributes to this topic and is focussed on the experiments reported in this thesis. Consequently, we concentrate on the psychomotoric aspects of the learning process. The educational situation in which a normal child learns to write a new allograph is chosen as an example and discussed in detail. The present-day educational situation without the assistance of a micro-computer is contrasted to a hypothetical situation in which a micro-computer is employed. We will start with a detailed description of the learning process in the primary stage of handwriting education in order to illustrate the complexity of the learning process and the problems presenting themselves to the teacher who wishes to observe and evaluate the movement production process.

Educational techniques used in primary handwriting education

At present, the primary stage of handwriting education is considered to be both the most important and the most complex stage. What techniques are available to the teacher in order to teach the children a new letter form? The attention of the children is drawn to the new letter form by means of various

activities or *orientation techniques*. The teacher will first draw the letter on the blackboard by means of arm movements. She will ask the children to imitate her arm movements (motoric orientation) and, subsequently, she will discuss the letter form in detail (verbal and visual orientation). She sometimes uses three-dimensional models of the letter to be touched (tactile orientation) or she refers to simple objects which can be associated with the letter form (associative orientation, e.g., an egg referring to the letter *o*). Finally, she may ask the children to search carefully for those points within the letter form at which the direction of movement changes. These points have to be connected in the first few attempts of writing the new letter. In the latter case the teacher uses the orientation technique which appeared to be an efficient one in the investigations of the Russian educationalist Pantina (1957). By means of these preliminary activities the child is supposed to have received enough information to prepare his first attempt to write the new letter. This attempt is usually made with a fountain-pen and consists of tracing a preprinted letter form in an exercise book. After tracing the letter several times, it has to be copied until it is mastered.

Processes involved in learning to write new letter forms

On the basis of his *task orientation* the child prepares a plan for movement. This plan probably contains abstract information concerning the order and the spatial relations of the strokes which have to be performed. The child may be presumed to have already adopted a writing posture which enables adequate performance. Depending on the age of the child and the perceived task demands, a certain level of muscular tension will develop. If a correct writing posture has been adopted, movements of the hand around the wrist joint will initiate movements in the rightward-upward direction and movements of the fingers will result in movements in the downward direction. Small finger movements will also result in small curvature changes within single strokes. The ratio of stroke lengths will be realized by varying the time interval during which the muscle groups responsible for stroke production are active and, to a lesser degree, by increasing the overall force level in these muscle groups. Tactile and kinaesthetic information perceived during the performance of the first few attempts will be used to develop coordinated control mechanisms of the involved muscle groups. Visual information will be used to correct performance during execution and to evaluate performance after the attempt. With an increasing number of attempts, writing size will decrease and the strokes will be positioned more consistently upon the line of writing. Stroke productions will become more fluent and regular with practice. The width and slant of the products will become more uniform across attempts. Penpoint pressure will gradually

decrease as the execution becomes more automatic and less dependent on tactile and kinaesthetic information. The ratio of the stroke lengths and the curvature of the strokes will gradually match the stroke-length ratio and stroke curvatures of the letter model to be mastered.

It will be clear that many processes occur while the movements of the first attempts in writing a new letter are executed by a pupil. At present, the teacher generally is not able to observe these processes. However, the recent technological developments which have made it possible to investigate the production of handwriting movements in detail might also be put to use in handwriting education in order to observe and evaluate the processes mentioned previously.

Future computer-assisted handwriting education

To the extent that computers might be used in future handwriting education, they need not be large. A micro-computer with a monitor, a digitizer and a pen containing a pressure sensor are sufficient for this purpose. The monitor, to be placed at a proper distance in front of the child, has a multi-purpose function. It can be used as an instrument for displaying the writing task in a dynamic mode. Søvik (1976) and Wright & Wright (1980) have shown that presenting information concerning the writing task which has to be performed in a dynamic way is more effective than presenting it in a static fashion as a finished product. The monitor might also be used to redisplay the performed writing attempt or to provide information concerning spatial and kinematic aspects of the writing attempt. The digitizer, or so-called writing tablet, and the pen, which is connected through a thin wire with the tablet, allow the recording of the position of the pen on the digitizer at a high frequency. During the performance of handwriting movements, the computer will normally record information regarding the location of the pen and the axial pressure exerted on the penpoint a hundred times per second (Maarse et al. 1985). In order to operate this equipment ergonomically we have suggested that a menu of options must be developed (Meulenbroek 1989). This menu has to be placed on the digitizer so that it can be used for a simple and direct interaction between the child and the computer. By touching specific areas of the menu with the pen, the child may indicate (1) the selection of a writing exercise, (2) the visual presentation of the selected exercise, (3) the moment at which he or she is prepared to make an attempt to perform the exercise, (4) the moment at which he or she is finished, (5) the moment at which he or she wants to review the attempt (6) the moment at which the presentation of feedback concerning the attempt is given. In first instance, the feedback might concern either spatial or kinematic characteristics of the writing movements. Spatial feedback must inform the

child whether a stroke sequence, letter or word is performed properly with regard to the characteristics of form, lineation, size and slant. Kinematic feedback must inform the child about the speed, pen-lifts, pen pressure or fluency. The computer program which in the future may be constructed might calculate these aspects on the basis of the recorded signals as follows. Once the child has performed a writing task, the recorded signals are preprocessed, i.e., filtered, in order to enhance the spatial and temporal resolution (Maarse et. al. 1985). Following this preprocessing, the program has to search immediately for the stroke boundaries (see e.g., chapter 2), e.g., by searching for the points in time where the absolute pen-point velocity reaches a local minimum. Having determined the points in time at which the strokes start and end, the program has to calculate the width, height, slant, length and curvature of the individual strokes. We also suggest that the program (1) must determine a code reflecting the spatial characteristics of the produced stroke sequence and (2) compare this code with a code representing the model sequence which was entered by the programmer. The latter code will of course contain spatial requirements of the writing pattern. Besides these spatial aspects, the program also must determine the kinematic performance measures such as the speed, fluency and pen pressure of the successive strokes and compare these measures with a current set of adapted criteria. The different forms of feedback will have to inform the child in a simple and understandable way whether or not the next attempt must be made at a different speed, more fluently or with less pen pressure.

In order to present information regarding the correctness of the form of stroke sequences, letters or words, the spatial aspects of the units will have to be formalized precisely. Educationalists and researchers must specify in a joint effort the spatial aspects of handwriting units that are most essential with regard to both the motoric production process and the legibility of the handwriting product. For example, the ratio of the length of the successive strokes of a unit has to be determined as well as the critical deviations from these ratios in order to decide whether the attempt of the child is to be regarded as correct or incorrect. The kinematic aspects of the production of strokes, allographs, and bigrams by primary-school children collected in the present series of experiments need to be extended by experiments revealing kinematic data concerning the production of words. Most aspects of the suggested computer-assisted training environment have been developed in our laboratory in order to conduct research and demonstrate our research approach. However, the proposed training situation has not yet been tested with regard to its educational value. Comparable computer-assisted training situations concerning handwriting have, however, been developed and tested in special-educational settings for deaf (Brooks & Newell 1985) and for blind

(Macleod, 1980) students. The effects of these training situations seem to be promising and they deserve to be investigated in future application-oriented research on more general forms of handwriting education and its remediation.

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Summary

This thesis consists of an empirical study of the production of handwriting movements. Six experiments are reported in which adult subjects and primary-school children performed writing tasks which systematically varied in complexity. The writing tasks are also educationally relevant. An important goal of this thesis is to make a contribution to the improvement of formal handwriting education. Chapter 1 describes the global structure and the contents of this thesis and contrasts the present study with studies in the field of handwriting development and education of the last three decades. It is concluded that the latter research highly depends on the subjective judgments of writing products. The research presented in this thesis, however, is based on the objective registration and the almost completely automatically performed analysis of handwriting movements by means of computer techniques. On the basis of the data resulting from these analyses, inferences are made with regard to information processes and movement strategies which are considered to underly the production of handwriting movements. Therefore, this dissertation focusses on processes rather than on products.

Chapter 1 presents a sequential-parallel model of the production of handwriting movements (Van Galen, Meulenbroek & Hylkema, 1986; Van Galen, Smyth, Meulenbroek & Hylkema, in press). This model is not explicitly investigated in this thesis but has strongly influenced the research questions and interpretations of the experimental results. Furthermore, some implications of the model for the organization and contents of handwriting curricula are pointed out in chapter 7 of this thesis. According to the model, which was originally developed by Van Galen (1980), a writer processes the representations of handwriting units at various levels. With regard to the handwriting units the model distinguishes three different levels. Word, letter and stroke representations are transformed in a specific hierarchical order before the activity in specific muscles results in up, down and progressing movements of the pen. The model also states that an experienced writer is able to process the representations of the different handwriting units simultaneously, i.e., in a parallel fashion. During the production of a specific handwriting stroke, the writer prepares the writing units of a higher order which have to be produced in the near future. On the one hand, the organization of this thesis corresponds globally to the information-processing stages which the model distinguishes. The production of stroke sequences, of single allographs, of bigrams and of words are successively investigated. On the other hand, the sequence of the chapters also corresponds to the order of tasks by means of which primary-school children are taught the skill of

cursive handwriting.

Chapter 2 discusses a reaction-time experiment concerning the production of line segments by adult subjects. The research questions are related to the identification of motor-preparation processes and the effects of variations in motoric activation preceding the production of line segments. Variations in the number, the length and the direction of the line segments to be produced result in independent variations in choice-reaction time. According to the additive-factor methodology of Sternberg (1969), these results imply that the motoric preparation in this task entails three different information-processing stages. These stages are involved in the preparational aspects of programming, parameterization and initiation, respectively. The experiment supports the independence of the last three stages of the previously mentioned model of Van Galen et al. (in press). In this model it is stated that the retrieval of a motor program from memory, the specification of force and time parameters within the program, and the selection of the adequate motor units in the nervous system, are three separate processes which precede the initiation of handwriting movements. Chapter 2 also provides empirical evidence indicating that variations in the global level of motoric activation, which was varied in the experiment by means of a fourth experimental variable, i.e., foreperiod duration, influences the stage in which the specification of movement parameters takes place. An overall change in muscle tension before a movement is initiated interacts with the setting of the force parameter determining the size or the length of a writing trajectory.

The chapters 3, 4 and 5 report experiments which took place in primary school. The research questions concern the motoric behaviour of pupils in preliminary, primary and advanced stages in handwriting education. Various complexity aspects relevant to handwriting development and instruction are investigated.

Chapter 3 reports a study of the production of stroke sequences, i.e., preparatory writing patterns, by 6 to 8 year-old primary-school children. The motoric complexity of loops, arcades, zig-zags and wave patterns is determined by means of an analysis of movement time, writing speed and signal-to-noise ratios of the amplitude-frequency spectrum of the absolute velocity of the writing movements. By means of this analysis, the quality of the stroke-production process in 6, 7 and 8 year-old pupils is investigated as well as the motoric effects of variations in pattern length, speed-accuracy instructions and lineation conditions. The results show a discontinuity in handwriting development. This discontinuity can be explained by the nature of the movement strategies which 6- to 8-year old children use while producing stroke sequences. Six-year-old children perform writing

movements in a fast, fluent, i.e., a ballistic fashion. Seven-year-old children move more slowly and less fluently, probably because they correct their movements frequently on the basis of sensory information. Eight-year-old children are able to integrate sensory feedback better, which results in an increase in speed and fluency. These results correspond to the findings of Hay (1979; 1984) and Von Hofsten (1979; 1980) with regard to the motoric development of reaching behaviour. This discontinuity in motor development is verified in experiment 2 of chapter 4 and in chapter 6.

Chapter 4 discusses two experiments concerning the production of single cursive allographs by 8 to 12-year-old primary-school children. In a reaction-time situation, the 26 allographs of our cursive alphabet are produced twice, once after the visual presentation of cursive stimulus letter and once after the visual presentation of printed ones. In the first experiment of chapter 4, the perceptual-motor complexity of letter forms is investigated by analyzing the reaction time, writing speed and fluency in which the cursive allographs were produced in the two stimulus conditions. The reaction-time difference per letter between the stimulus conditions is considered to be an index of the complexity of the allograph-selection process, i.e., the time needed by the subject to produce a cursive allograph after the presentation of a printed stimulus letter. The results show that spatial and contextual ambiguity, allographic variability and letter frequency are four factors which exert an influence on the allograph-selection process. The motoric complexity of cursive allographs appears to be mainly dependent on the curvature of letter segments. Experiment 1 of chapter 4 is followed by a discussion of a number of practical implications of the results to the sequence and forms of letters in handwriting curricula. Experiment 2 of chapter 4 is a more detailed verification of the discontinuity in motor development found in chapter 3. The data of experiment 1 of chapter 4 are analyzed from a different viewpoint. A trend analysis on the writing speed and fluency in which 8 to 12-year-old pupils produced single cursive allographs shows, besides a linear, also a significant cubic age-dependent component. These results, as in chapter 3, are interpreted by assuming that in the initial stage of learning a complex motor task, ballistic movement strategies underly performance. In a following learning stage, sensory information is frequently used to control the production of movements and speed and fluency decrease. Finally, in a third learning stage, these strategies are probably integrated which accounts for the increase of movement quality.

Chapter 5 describes an experiment concerning the production of connecting strokes in cursive bigrams by 8- to 12-year-old pupils. The hypothesis is formulated that the production of letter connections is a specific motoric process to be distinguished from the production of within-letter

strokes. An analysis of movement time, distance and velocity, an analysis of frequency spectra of tangential velocity profiles and a spatial analysis of the within-subject variance and between-subject variability of comparable upstrokes within and between letters confirm this hypothesis. The exact form of letter connections is probably determined locally, and not on the basis of information retrieved from motor memory. Chapter 5, therefore, indirectly provides evidence for the viewpoint that, within motor memory, motor programs are stored which contain abstract information concerning the allographs being the important representational units.

Chapter 6 concerns a study of variations in handwriting movements produced by right and lefthanded adult subjects. Besides effects of handedness, effects of postural differences and effects of gender are investigated. The writing tasks entailed the production of stroke sequences and words of varying length. An analysis of kinematic and spatial aspects of the handwriting movements reveals that, at the levels of stroke production and letter production, hardly any motoric differences exist between righthanders, lefthanders who place the hand above the line of writing and lefthanders who place the hand beneath the line of writing. Both groups of lefthanders, however, lift the pen more often during the production of longer words. Although earlier experiments have shown that in primary handwriting education the non-inverted hand posture in lefthanders leads to better learning results than the inverted hand posture, the present results show that at a later age the former hand posture may be considered as a functional adaptation to the global left-to-right direction in which in our culture the words are formed and placed on the line of writing.

This thesis ends with a seventh chapter containing an epilogue in which some implications and applications of the present study to the field of handwriting education are discussed. The sequential-parallel model of the production of handwriting movements discussed in this thesis implies that in handwriting curricula instructional techniques should be used which also train the preparational process, being a necessary requirement for the efficient production of writing movements. The results of the studies reported in the chapters 3 to 6 provide direct implications concerning the sequence of preparatory writing patterns, allographs and bigrams, aspects of form of these writing units, the instructional techniques by means of which handwriting can be optimally trained, and the evaluation of handwriting performance in educational settings. Finally, the epilogue describes a learning situation which might be educationally relevant in the near future as far as the treatment of writing problems is concerned. In this learning situation a pupil practises writing tasks with an electronic pen, an XY tablet and a micro computer. Consequently, it will be possible to provide the pupil with detailed

information regarding one or more (of an in principle large variety of) aspects of his or her writing movements.

Samenvatting

Dit proefschrift bevat een empirisch onderzoek naar de productie van schrijfbewegingen. Een zestal experimenten wordt beschreven waarin volwassen proefpersonen en basisschoolleerlingen schrijftaken uitvoeren van systematisch gevarieerde complexiteit. De schrijftaken zijn tevens relevant voor de praktijk van het schrijfonderwijs. Een belangrijk doel van dit proefschrift is dan ook een bijdrage te leveren aan de verbetering van het formele schrijfonderwijs. Hoofdstuk 1 beschrijft de globale structuur en de inhoud van dit proefschrift en maakt vergelijkingen met onderzoek op het gebied van de schrijfontwikkeling en het schrijfonderwijs van de laatste drie decennia. Geconcludeerd wordt dat het laatstgenoemde onderzoek in hoge mate steunt op subjectieve beoordelingen van schrijfproducten. Het onderzoek van deze dissertatie is echter gebaseerd op de objectieve registratie en de grotendeels geautomatiseerde analyse van schrijfbewegingen met behulp van computertechnieken. Op basis van de hiermee verkregen gegevens worden uitspraken gedaan over informatieverwerkingsprocessen en bewegingsstrategieën die geacht kunnen worden ten grondslag te liggen aan de productie van schrijfbewegingen. Deze dissertatie is dan ook op processen gericht veeleer dan op producten.

Hoofdstuk 1 behandelt een sequentieel-parallel model van de productie van schrijfbewegingen (Van Galen, Meulenbroek & Hylkema, 1986; Van Galen, Smyth, Meulenbroek & Hylkema, in druk). Dit model wordt niet expliciet in dit proefschrift getoetst maar heeft in hoge mate de vraagstellingen en de interpretaties van de onderzoeksresultaten beïnvloed. Enkele implicaties van het model voor de opbouw en de inhoud van schrijfcurricula worden voorts in hoofdstuk 7 van dit proefschrift beschreven. Volgens het model, dat in aanzet ontwikkeld werd door Van Galen (1980), verwerkt een schrijver op verschillende niveaus de interne representaties van schrijfeenheden. Het model onderscheidt drie verschillende eenheden. Woord-, letter-, en haalrepresentaties worden in een specifieke hiërarchische volgorde getransformeerd alvorens uiteindelijk de activiteit in bepaalde spieren resulteert in op-, neer- en voortgaande bewegingen van de pen. Tevens stelt het model dat een geoefend schrijver in staat is op verschillende niveaus de transformaties van de representaties van verschillende eenheden van handschrift tegelijkertijd, dus parallel, uit te voeren. Tijdens de productie van een specifieke schrijfhaal prepareert de schrijver de in de nabije toekomst nog te produceren schrijfeenheden van hogere orde. De opbouw van dit proefschrift komt in grote lijnen nauw overeen met de informatieverwerkingsniveaus die het model onderscheidt. Achtereenvolgens komt de productie van haalsequenties, van enkelvoudige lettervormen, van

cursieve bigrammen, en tenslotte van woorden aan de orde. Anderzijds corresponderen de opeenvolgende hoofdstukken ook globaal met de taakvolgorde waarin leerlingen in de basisschool het verbonden schrift aanleren.

Hoofdstuk 2 bespreekt een reactietijd-onderzoek naar de productie van lijnsegmenten door volwassen proefpersonen. De onderzoeksvraagstelling betreft de identificatie van motorische preparatieprocessen en de effecten van globale variaties in de motorische activatie voorafgaande aan de productie van lijnsegmenten. Variaties in het aantal, de lengte en de richting van de te schrijven lijnsegmenten resulteren in onafhankelijke variaties in keuze-reactietijden. Volgens de additieve-factoren logica van Sternberg (1969) impliceren deze bevindingen dat de motorische preparatie van deze taak tenminste drie verschillende informatie-verwerkingsstadia omvat. Deze stadia zijn dan respectievelijk betrokken bij de programmerings-, de parameterizatie- en de initiatie-aspecten van de preparatie. Het onderzoek ondersteunt aldus de onafhankelijkheid van de laatste drie stadia van het eerder aangeduide model van Van Galen e.a. (in druk). Hierin wordt gesteld dat het ophalen van een motorisch programma uit het geheugen, het instellen van de kracht- en tijdsparameters in dit programma, en het kiezen van de juiste motorische eenheden in het zenuwstelsel, drie aparte processen zijn die voorafgaan aan de initiatie van schrijfbewegingen. Hoofdstuk 2 levert tevens empirische evidentie dat variaties in het algemene motorische preparatieniveau, in het onderzoek gemanipuleerd door variaties van een vierde variabele, n.l. voorperiode-duur, aangrijpt op het stadium van het instellen van de bewegingsparameters. Verandering in de globale spierspanning voordat een beweging wordt geïnitieerd interacteert met de ingestelde krachtparameter die de bewegingsafstand, ofwel de lengte van een schrijftraject, bepaalt.

De hoofdstukken 3, 4 en 5 betreffen experimenten die hebben plaatsgevonden in de basisschool. De onderzoeksvraagstellingen betreffen het motorisch gedrag van leerlingen in respectievelijk het voorbereidend, het aanvankelijk en het voortgezet schrijfonderwijs. Onderzocht worden diverse complexiteitsaspecten die relevant zijn in het licht van de schrijfmotorische ontwikkeling enerzijds en de schrijfinstructie anderzijds.

Hoofdstuk 3 rapporteert een onderzoek naar de productie van haalsequenties, dat wil zeggen voorbereidende schrijfpatronen, door 6- tot 8-jarige basisschool-leerlingen. De motorische complexiteit van guirlanden, arcaden, het zig-zag patroon, en het golfpatroon, wordt vastgesteld door een analyse van bewegingstijden, snelheden en signaal-ruisverhoudingen in het amplitude-frequentie spectrum van de absolute snelheid van de

schrijfbewegingen. Met deze analyse wordt tevens de kwaliteit van het haalproductie proces van 6-, 7- en 8-jarige leerlingen onderzocht en worden de motorische effecten van lengte-, snelheids- en nauwkeurigheidsinstructies en van lineatuurcondities nagegaan. De resultaten tonen een discontinuïteit in de schrijfmotorische ontwikkeling. Deze discontinuïteit kan verklaard worden door de aard van de bewegingsstrategieën die 6- tot 8-jarigen hanteren bij het produceren van haalsequenties. Zesjarigen voeren schrijfbewegingen op een snelle, vloeiende, d.w.z. ballistische, manier uit. Zevenjarigen bewegen trager en minder vloeiend, waarschijnlijk doordat ze hun bewegingen in toenemende mate sturen op basis van sensorische informatie. Achtjarigen kunnen door verdergaande oefening deze terugkoppeling beter integreren hetgeen resulteert in een toename van de snelheid en vloeiendheid. De resultaten komen overeen met bevindingen van Hay (1979; 1984) en Von Hofsten (1979; 1980) met betrekking tot de motorische ontwikkeling van reik- en grijpbewegingen. De discontinuïteit in de schrijfmotorische ontwikkeling wordt in experiment 2 van hoofdstuk 4 en in hoofdstuk 6 gerepliceerd.

Hoofdstuk 4 bespreekt twee experimenten betreffende de productie van enkelvoudige cursieve lettervormen door 8- tot 12-jarige basisschoolleerlingen. In een reactietijdsituatie worden de 26 letters van een cursief schrijffalfabet twee maal geproduceerd, eenmaal na de visuele aanbieding van cursieve letters en eenmaal na de visuele aanbieding van drukletters. In het eerste experiment van hoofdstuk 4 wordt de perceptuo-motorische complexiteit van lettervormen onderzocht door de reactietijd, de schrijfsnelheid en de vloeiendheid waarmee de cursieve letters in de twee aanbiedingscondities werden geproduceerd te analyseren. Het verschil in reactietijd per letter tussen de twee aanbiedingscondities wordt beschouwd als een index voor de complexiteit van het allograaf-selectie proces, d.w.z. de tijd die de proefpersoon nodig heeft om op basis van een visueel aangeboden drukletter de productie van een corresponderende schrijffletter te initiëren. De resultaten tonen dat spatiële en contextuele ambiguïteit, allografische variabiliteit en letterfrequenties vier factoren zijn die invloed hebben op het allograaf-selectie proces. De motorische complexiteit van cursieve lettervormen blijkt voornamelijk afhankelijk te zijn van de kromming van lettersegmenten. Experiment 1 van hoofdstuk 4 wordt gevolgd door de bespreking van een aantal praktische implicaties van de resultaten voor geschikte lettervolgorden en lettervormen in schrijfcurricula. Experiment 2 van hoofdstuk 4 vormt een nader onderzoek van de in hoofdstuk 3 gevonden discontinuïteit in de schrijfmotorische ontwikkeling. De data van experiment 1 van hoofdstuk 4 worden geanalyseerd vanuit een ander gezichtspunt. Een trendanalyse op de bewegingssnelheid en de vloeiendheid waarmee 8- tot

12-jarige leerlingen enkelvoudige cursieve lettervormen produceren vertoont, naast een lineaire, een significante kubische leeftijdsafhankelijke component. De resultaten worden evenals in hoofdstuk 3 geïnterpreteerd in het licht van de veronderstelling dat in een eerste fase van het leren van een complexe motorische vaardigheid ballistische bewegingsstrategieën worden gehanteerd. In een tweede leerfase stuurt sensorische informatie de bewegingen waardoor de snelheid en vloeiendheid afneemt. In een derde leerfase, tenslotte, worden deze strategieën geïntegreerd zodat de kwaliteit van de bewegingen toeneemt.

Hoofdstuk 5 behelst een onderzoek naar de productie van verbindingshalen in cursieve bigrammen door 8- tot 12-jarige leerlingen. Vanuit theoretische argumenten wordt de hypothese onderbouwd dat het verbinden van letters een specifiek motorisch productieproces is dat zich onderscheidt van de productie van de op- en neerhalen binnen letters. Een analyse van bewegingstijden, afstanden en snelheden, een analyse van frequentiespectra van tangentiële snelheidsprofielen en een spatiële analyse van zowel de variantie binnen subjecten als de variabiliteit tussen subjecten betreffende de vorm van vergelijkbare ophalen binnen letters en tussen letters bevestigen de hypothese. Letterverbindingen worden waarschijnlijk qua vorm ad hoc berekend en niet vanuit motorische geheugenprogramma's geproduceerd. Hoofdstuk 5 levert hierdoor indirecte evidentie voor het inzicht dat in het motorisch geheugen programma's liggen opgeslagen die op een abstracte manier informatie bevatten over de allografische lettervormen als schrijfeenheden.

Hoofdstuk 6 omvat een onderzoek naar verschillen tussen de schrijfbewegingen van rechts- en linkshandige volwassen proefpersonen. Naast handvoorkeur worden ook handpositie en sexe-verschillen onderzocht. De schrijftaken betroffen het produceren van haalsequenties en woorden van verschillende lengte. Een analyse van de kinematische en spatiële aspecten van de schrijfbewegingen laat zien dat op het nivo van haal- en letterproducties er slechts of helemaal geen motorische verschillen bestaan tussen rechtshandigen, linkshandigen die de hand boven de regel positioneren, en linkshandigen die de hand onder de regel plaatsen. Beide groepen linkshandigen tillen de pen echter wel vaker op bij het schrijven van langere woorden. Linkshandigheid vergt daarom een speciale organisatie van de werkruimte. Hoewel uit ander onderzoek blijkt dat bij linkshandigen een positionering van de hand onder de regel in het aanvankelijk schrijfonderwijs leidt tot betere schrijfsresultaten dan een positionering van de hand boven de regel, tonen de resultaten van deze studie dat op latere leeftijd de laatstgenoemde positie beschouwd kan worden als een functionele adaptatie aan de globale links-rechts richting waarin in onze cultuur de woorden worden

gevormd en na elkaar op de regel worden geplaatst.

Dit proefschrift wordt afgesloten met een epiloog in hoofdstuk 7, waarin enkele implicaties en applicaties van het in dit proefschrift gerapporteerde onderzoek voor het schrijfonderwijs worden uiteengezet. Het gehanteerde sequentieel-parallele model van de productie van schrijfbewegingen impliceert dat in schrijfcurricula instructie-technieken gebruikt dienen te worden waarmee ook de preparatieprocessen worden geoefend die een voorwaarde vormen voor de efficiëntie van de productie van schrijfbewegingen. De resultaten van de studies gepresenteerd in de hoofdstukken 3 tot 6 leveren directe aanwijzingen op omtrent de volgorde van schrijfpatronen, lettervormen en bigrammen, de vormaspecten van deze schrijfeenheden, de instructie-technieken waarmee schrijven in de basisschool het beste geoefend kan worden en omtrent de motorische evaluatie van schrijfprestaties in het onderwijs. Tenslotte wordt in de epiloog een leersituatie beschreven die in de nabije toekomst van belang kan zijn voor de remediëring van schrijfproblemen. In deze leer-'omgeving' oefent een leerling schrijftaken met een elektronische pen, een XY-tablet en een microcomputer. Hierdoor wordt het mogelijk de leerling over één of enkele (van een in beginsel een zeer groot aantal) aspecten van zijn schrijfbewegingen vrijwel onmiddellijk zeer nauwkeurige informatie te verschaffen.

Curriculum vitae

Ruud Gerardus Johannes Meulenbroek werd geboren te Middelburg op 27 juli 1958. Vanaf 1970 volgde hij VWO (B), eerst vier jaar te Goes, en vervolgens twee jaar te Breda. Van 1976 tot 1979 studeerde hij psychologie aan de Katholieke Hogeschool Tilburg. Na het kandidaatsexamen aldaar vervolgde hij zijn studie aan de Katholieke Universiteit Nijmegen waar hij in 1983 het doctoraal examen psychologie behaalde in de Psychologische Functie-leer met als specialisatie motoriek. Het onderwerp van zijn afstuderen was programmering, parameterisatie en initiatie van schrijfbewegingen. In 1984 organiseerde hij met Prof. Dr. A.J.W.M. Thomassen een nationaal symposium over "Toegepaste aspecten van de schrijfmotoriek". Van november 1984 tot juli 1988 was hij werkzaam op een door de Universitaire Onderzoekpool gesubsidieerd project betreffende hetzelfde onderwerp. Dit project leidde tot het huidige proefschrift. Behalve in artikelvorm werd over de resultaten van dit project tussen 1985 en 1988 gerapporteerd op congressen en symposia te Brighton, Montreal, Keulen, Antwerpen en Nijmegen. Vanaf juli 1988 is hij binnen het NICI als 'ervaren onderzoeker' belast met de uitvoering van een door NWO gesubsidieerd project getiteld "Grafische productie".

