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Handwriting: Issues for a psychomotor theory *

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Abstract

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In this article it is argued that handwriting basically is a multi-component task. This implies that the production of writing strokes is the overt manifestation of divergent cognitive, psychomotor and biophysical processes. Based upon a review of elementary psychomotor findings and theoretical issues related to the cognitive structure of the skill, a possible architecture for handwriting processes is sketched. In this handwriting model each process has a characteristic unit of processing; receives its input from the operation next higher in the hierarchy; and is responsible for a specific transformation of that information to make it appropriate as an input to the next lower process. To accommodate for processing time frictions between modules, each of them is assumed to have a provision for a transient storage of output. The parallel feature of the model involves that all processors operate concurrently, but on different features of the message.

Handwriting: A complex cognitive skill

The usage of artifacts to communicate feelings and meanings to members of the group is an exclusive expedient of Homo Sapiens. About 35,000 years ago, humans began to create symbols of themselves, of the animals around them, and perhaps of the passage of time (Putman 1989). Archaeologists date the first carved symbols that form the origin of modern handwriting about 10,000 years ago (Gelb 1952).

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For the evolution of handwriting in human society at least three indispensable requirements have to be fulfilled: the evolution of a cognitive skill to use signs as carriers of meaning, craftmanship to use 'writing' utensils and materials to 'write' upon, and the emergence of a social organization that produces a need for lasting and controllable forms of communication. The latter condition may be recognized within the culture of the ancient Sumerians who invented the hieroglyphics, and among the trade faring Phoeniciens who can be credited for the development and distribution of an alphabetic system of writing in the Western part of the ancient world (Milone 1984).

The appearance of handwriting in the history of mankind is relatively late. Also, along the ontogenetic time scale the skill develops relatively late. In most literate societies children start to write after 6 years of age, and an adult writing speed is only achieved at about 15 years (Sassoon et al. 1986). This is long after children start to walk, to speak, to draw, to play musical instruments, and to perform sports skills. Handwriting typically is a compound, cognitive and motor skill. As it is presently used in Western countries, writing is based on semantic and lexical knowledge; in alphabetical writing, moreover, the writer has to deal with the often complex relations between a language-specific set of phonemes and the set of letters (or 'graphemes') used in the alphabet. This task is often complicated by varied phonological mapping rules, and by non-phonological spelling prescriptions. Further, not only different allographic forms for upper and lower case script have to be learned, but many educational systems confront the child with a variety of writing modes like cursive script, manuscript style and print letters. Whereas the mastery of the alphabet and elementaries of spelling may be considered as necessary for the skill of reading as well, handwriting further requires a very delicate manipulation of the pencil in order to draw specific forms, with a specific orientation and size, at specific positions of a writing surface.

Earlier surveys on handwriting research concentrated on selected, mostly educational and developmental aspects of acquisition of the skill, and upon ergonomical features of writing techniques (Barbe et al. 1984; Søvik 1975). Askov et al. (1970), in reviewing the 1960–70 decade, classified handwriting research according to seven categories, suggested earlier by Herrick and Okada (1963). Basically, research in handwriting was concerned with the following topics: efficiency and legibility of letter forms, ergonomic aspects of body posture and penholds, the nature of handwriting tools and writing surfaces, effects of speed and stress on the handwriting product, developmental and instructional principles involved in the acquisition of the skill, organization of the handwriting curriculum in primary school, and research on scales to assess the quality of handwriting performance. Ten years later, Peck et al. (1980) produced another survey of progress and prospects that, again, was organized according to the same topics.

In recent years we saw a shift from a *product-oriented* to a *process-oriented* approach to handwriting (Kao et al. 1986; Plamondon et al. 1989; Thomassen et al. 1984), although its roots reach beyond the eighties (Denier van der Gon and Thuring 1965; Vredenbregt and Koster 1971; Wing 1978). Contributions for an understanding of handwriting as a cognitive and motor process came from experiments on latencies and movement times in handwriting tasks (Hulstijn and Van Galen 1983; Van Galen and Teulings 1983; Stelmach and Teulings 1983), from neuropsychological observations on disturbances of handwriting related to localized brain lesions (Ellis 1982, 1988; Margolin 1984), and from mathematical models of trajectory formation (Edelman and Flash 1987; Hollerbach 1981; Plamondon and Maarse 1989). Many of these studies became feasible only after electronic digitizer tablets enabled researchers to trace real-time dynamics of handwriting production (Teulings and Maarse 1984; Teulings and Thomassen 1979).

Some facts and their meaning for a theory of handwriting

One of the characteristic features of handwriting, and making it partly different from speech and typewriting, is that writing movements are produced in a predominantly serial way. Letter strokes are produced one by one, and letters are formed through the serial concatenation of strokes. Letters again are produced one by one to form words and phrases. From an anatomical point of view, adult writers mostly produce script through the combined operation of finger, wrist and arm movements. Roughly speaking it may be said that strokes with a left to right orientation and horizontal relocations of the hand along the line of writing are produced through ulnar abductions of the wrist, whereas vertical strokes and trajectories with a high degree of curvature are more strongly dependent upon the involvement of finger flexions and extensions. A greater anatomical complexity of the finger system, as it requires the simultaneous control of a greater number of joints, has sometimes been invoked to explain the smaller efficiency in terms of movement time and fluency of vertical strokes (Meulenbroek and Van Galen 1986). However, there is a tremendous variety between individuals, between writing tasks and even between the production of script at different places in the writing plane, with regard to the involvement of specific parts of the muscular system. Handwriting certainly is one of the most striking examples of a task characterized by a high degree of *motor equivalence* (Bernstein 1967), a concept which is exemplified by the finding of constancy of letter forms and writing slant when writing tasks are performed with different limbs and writing instruments (Maarse et al. 1986; Merton 1972; Thomassen and Teulings 1983).

Handwriting is characterized by motor equivalence in its dynamic aspects as well. The latter means that there is no single and simple answer to the question whether it is the amplitude of force, force duration or a combination of both which is monitored by the motor system in controlling form and size of script. Wing (1980) produced evidence for a dissociation between the production of height variations *within* and *between* words. Within-word height variations, as between *e* and *l*, seemed predominantly to be realized by an adjustment of the duration of the agonist force burst. Between word height variation, as in the word *elegy* written small or large, could be attributed to a variation of the *time interval* between agonist and antagonist onset. Wing suggested that overall writing size, and stroke sizes used to discriminate letter forms, were controlled by two different mechanisms. In later studies it turned out that the picture is even more complicated, and that a considerable number of different physical models can be formulated which more or less satisfactorily describe the production of writing strokes (Maarse et al. 1989). Teulings et al. (1986) compared constancy of spatial, temporal and force amplitude parameters across writing tasks. They concluded that handwriting is most constant with regard to *spatial* features, whereas *force amplitude* is traded off against *force duration* in order to achieve such spatial constancy. Just as for the anatomically defined motor equivalence, it is claimed that human subjects control abstract, spatial features of script, whereas the motor system proper uses distributed, coordinative structures to maintain motor equivalence in an ever varying biophysical context. In essence, we defend a hierarchical view on the generation of script. At the highest and most invariant level, subjects store and activate spatial codes of letter forms. At a lower level, appropriate force–time impulses are generated, reckoning with the real-time biophysical context. This approach differs from models of trajectory formation in which letter forms are stored as series of force–time pulses (Vredenbregt and Koster 1971; Hollerbach 1981).

A further demonstration of the abstract nature of spatial references in handwriting is found in studies on so-called main axes of writing. When polar vector plots are derived from an individual's handwriting non-homogeneous distributions of stroke directions are found (Maarse 1987). Typically, the vector plots demonstrate two predominant orientations. One of these is related to upstrokes and is predominantly involved in the left-to-right positioning of script. The other dominant direction corresponds to the average orientation of downstrokes. These are relatively most important for the formation of letter forms. The bipolar nature of this vector distribution has inspired several authors to think of the production of handwriting in terms of a perpendicularly oriented system of force generators (Denier van der Gon and Thuring 1965; Vredenbregt and Koster 1971) or springs (Hollerbach 1981). The idea of orthogonal force generators is attractive for several reasons: (1) the model is easily related to the complementary relationship between wrist excursions, and flexions and extensions of the finger system, which constitutes a nearly orthogonally operating production system in spontaneous script; (2) the assumption that a writtten trajectory is the joint product of two a priori completely independent subsystems makes the model highly efficient; (3) the model is easily related to the data structure produced by digitizer tablets, and (4) trajectory formation is easily simulated in the model. It should be mentioned, however, that in natural handwriting the angle between both axes is seldom orthogonal, and that the relation between the orientation of writing strokes and the muscular system is generally complex and variable. This implies that the principle of motor equivalence also applies to the maintenance of predominant directions in script (Teulings et al. 1989; Meulenbroek and Thomassen, this issue). The latter authors conclude that predominant directions are better understood as abstract axes of reference, to which the ongoing production of writing strokes is anchored, in spite of great variations of anatomical and biophysical conditions. Again, this interpretation seems to corroborate our stance that in handwriting invariant, spatial features substantiate the anchoring points for the more variable, dynamic parameters.

There are only a few studies related to the role of pengrips, but also for this task aspect the scarce evidence seems to support the idea of motor equivalence. Sassoon et al. (1986) found that, although there is a great anatomical variety of pengrips, writing proficiency is not strongly related to specific grips.

Also handedness does not seem to have a significant influence on the efficiency of writing. Meulenbroek and Van Galen (1989) studied spatial and dynamic characteristics of handwriting in right-handers, left-handers with an inverted ('hooked') pengrip, and non-inverted left-handers, with male and female subjects in all groups. Gender had a significant impact on writing speed and pressure, both being higher for men. Small spatial variations in letter slant and size were observed in lefthanders, apparently to be explained as ergonomic adaptations to the specific position of the hand. Similarly to findings by Peters and McGrory (1987), no differences in writing effiency, in terms of speed and fluency, were recorded.

Writing pressure is a less well studied parameter of script. Until now there is no generally accepted theory on the relation between writing pressure and psychological task factors. There are some interesting observations made by Kao (1983) about the progressive pressure increase towards the end of words, and by Schomaker and Plamondon (1990) on the relation between axial pen force and pen point kinematics. Furthermore, some developmental studies on writing pressure have been performed by Mojet (1989) showing a progressive pressure decrease with increase of age. The interpretation of these findings is complicated by the fact that writing pressure is contaminated with friction between the planar surface and the writing instrument (Wann and Nimmo-Smith, this issue).

Most often psychomotor studies of handwriting are based on time-dependent sampling procedures involving the spatial coordinates of the position of the tip of an electronically monitored writing instrument with which a subject performs writing tasks on the surface of a digitizer tablet. It should be realized that such data give a restricted representation of the complex skill of writing. Pengrip, arm, head and body movements to support the writing hand, and space-oriented behaviour above the tablet are often not represented in these data. Nevertheless, the digitizer tablet has provided numerous data on relevant issues of the skill. Given the first order spatial coordinates, a manyfold of higher order derivatives have been used in handwriting research. Among such measures are writing size, slant, average curvature, maximum and minimum curvature used as a measure of 'roundedness', horizontal progression, vertical deviation from the line of writing, linear and angular velocity and acceleration. The latter measure is often used as an estimate of the muscular forces involved in the production of script. As yet, a representative data base on dynamic features of average script within a population has not been published. From the experimental literature, however, some indicatory data can be derived. Teulings and Thomassen (1979) applied power spectral density analysis to samples of handwriting. In their report most of the variance related to the frequency spectrum of handwriting movements is restricted between 0.5 and 10 Hz. Apart from a relatively predominant frequency of about 5 Hz (which corresponds to a prevalent stroke duration of 100 ms) the spectral density function has a rather flat distribution. The latter means that movement times for separate strokes are highly variable, probably because of local demands such as curvature, length, character of ensuing stroke, serial position within a word, and other biomechanical and cognitive factors. In more restricted tasks such as writing single words typical stroke durations vary between 100 and 200 ms (a stroke being defined as a writing trajectory lying between two consecutive zero crossings of the vertical velocity function; this definition, however, is quite arbitrary).

A consistent finding with regard to spatial and temporal parameters of script is that they not merely reflect the biomechanical conditions of a given trajectory: movement time, writing size, writing fluency and other parameters have been shown to vary also as a function of cognitive and motor demands of the task. This has been shown not only for the production of discourse (Brown et al. 1988, 1989) but also for word length and serial position of letters within words (Van Galen et al. 1986), stroke and letter repetition (Van Galen et al. 1989), the phonological structure of words (Van Galen 1990), and spatial demands related to the performance of between-word spaces (Van der Plaats and Van Galen 1990). In most of the studies cited an increase of movement time and trajectory length has been interpreted as reflecting the sharing of processing resources between real-time stroke production processes and concurrent preparatory processes concerning forthcoming task segments. But alternative explanations related to movement *strategies* should be considered as well. One strategy, described by Viviani and Terzuolo (1980), and by Lacquaniti et al. (1983), is to hold the angular velocity of writing movements constant. A more detailed account of time and space invariances at word, letter and stroke level in handwriting has been presented by Thomassen and Teulings (1985). In some studies (Van Galen 1990; Van der Plaats and Van Galen 1990) it has been found that subjects tend to use specific strategies with respect to the distribution of space and time across consecutive words in the same task. When longer and shorter words have to be written within one single session, longer words tend to be speeded up and their letter size tends to be decreased. It was proposed that this strategy was another manifestation of motor constancy, now defined as the tendency to use equal time and space in varying task conditions.

Towards a cognitive theory of handwriting

Although recently some attempt has been made to simulate trajectory formation as well as cognitive processes in a single computational model (Schomaker et al. 1989), it will be clear that no single model of handwriting can convey all its biophysical and psychological aspects. Thus far, however, most models have concentrated on one single or a small number of task aspects, mostly related to the simulation of the biophysical realization of stroke production. Maarse (1987) discriminated between *micro* and *macro* models of handwriting. Micro models are concerned with the more peripheral and biophysical features of the generation of script. It can be stated that the main issue for such models is to describe how, given the principles of motor constancy as indicated above and given the biophysical constraints of the effector systems, strokes and concatenations of strokes are generated. Macro models, on the other hand, aim at describing the cognitive processes that provide the linguistic and motor goals for real-time trajectory formation. With regard to micro models, recently, Maarse et al. (1989), and Plamondon and Maarse (1989) have presented comprehensive reviews. In the present article, therefore, I will focus on findings relevant for the design of a *cognitive model* of handwriting.

Three basic questions have played a major role in cognitive studies of handwriting. These are; (1) What is the unit of processing in the preparation of handwriting tasks? (2) What empirical evidence is presently available to make relevant distinctions among the processes that contribute to the production of script. (3) How do preparatory programming stages relate to real-time stroke production?

In the following sections empirical evidence related to each of these questions is reviewed. The outcome of this survey is used to define the basic elements of a model of handwriting, which is sketched in the final section of this article.

On the variable size of the unit of programming

An early attempt to specify a unit of programming in handwriting was made by Wing (1978). He measured the durations of consecutive downstrokes and upstrokes in replications of the cursive letters *v*, *n*, *w*, and *m* to test whether the generation of handwriting strokes obeyed a time-based tapping model. If strokes were the programming units for such a mechanism, then the durations of consecutive strokes should correlate negatively, just as the consecutive tap durations in tapping tasks display negative correlations (Wing and Kristofferson 1973). The results revealed a negative correlation only between the first and second stroke, and positive correlations for all other stroke pairs, especially for the second and third stroke of *n*, *m*, and *w*. Thus, handwriting appeared not to obey a stroke-based timing structure. Wing's data suggested that, instead of single strokes, arcades, i.e. pairs of up- and downstrokes might constitute the units for the timing process. The latter notion, however, was not confirmed in a study on the same question by Teulings et al. (1986).

In a choice reaction time experiment, with pairs of letters to be written as quickly as possible, Teulings et al. (1983) tested whether the effects of precueing the identity of one or both of the letters favoured either strokes or complete letters as the unit of programming. Letter pairs consisted of either pairs of identical letters, or of letters with similar strokes, or of dissimilar letters. It was expected that if separate strokes were the units of programming, precueing the identity of a second letter of a *similar* pair should facilitate the initiation of that letter pair as much as precueing the second of an *identical* pair. If, on the other hand, complete letters constituted a programming unit, only precueing a second, identical letter should facilitate the initiation of writing. The results strongly supported the second view, i.e. in presetting the motor system for an upcoming handwriting response, complete letters seemed to be the programming units.

A different approach to the specification of programming units in handwriting was followed by Teulings et al. (1986), and by Hulstijn and Van Galen (1983, 1988). These studies were intended to test the subprogram retrieval model of Sternberg et al. (1978, 1980) for handwriting tasks. A short discussion of the model might be useful because the search for an elementary unit of programming is intimately related to the modelling of the programming system proper. The model assumes that the dimensions of an output string are prepared in a prescribed order, partly in advance of, and partly on line with task execution. For example, a string of five two-syllable words is represented as five stress groups which form the basic elements at the most abstract level of the motor program. The *number* of these elements, and not the motor complexity of the string, determine the time needed to initiate the string. Reaction time is only further incremented by the time needed by the next lower level of the system to retrieve the first word and to 'unpack' the first of the two syllables to be spoken. The subsequent programming steps are run during real-time execution of the speech task. After the initiation of the response, consecutive response units are retrieved from the representation of the response string in a temporary motor buffer. The model predicts that reaction times linearly increase with the number of stress groups, irrespective of their motoric complexity. Movement time plotted against sequence length, however, should be composed of a linear component related to the number of response units, and a quadratic component which originates from the increasing retrieval time for each response unit when the total number of response units in the motor buffer increases. Teulings et al. (1986) tested the subprogram-retrieval model with graphic tasks in which the number of strokes was varied. In none of the experiments an increase of movement time per stroke was found as a function of sequence length. Teulings et al. concluded that 'there is no one, single unit of programming in handwriting; instead the production units may depend upon the form of the output' (1986: 31).

Hulstijn and Van Galen (1983) tested the subprogram-retrieval model with several types of handwriting tasks. In one experiment, sequence length was varied through the number of letters, ranging between 1 and 4, together with variation of the length of each letter in terms of the number of strokes, and of the instructed writing size. The results showed that, in deviation of what has been reported for Sternberg et al.'s (1978; 1980) speech and typewriting tasks, writing one single symbol led to longer RTs than initiating a string of two or three symbols, especially when subjects were inexperienced with the task. When tested for sequence lengths of two and more symbols, reaction times, indeed, revealed a linearly increasing trend. But, at the same time, it appeared that the slope of this increase was quite small; after some training the rate of the slope was less than 2.0 ms/symbol, compared to 10 ms/unit reported by Sternberg et al. (1980). Moreover, the slope decreased greatly from the first to the final session, and it was significantly steeper for writing tasks with a physically longer trajectory (strings composed of 'long' letters, and strings composed of 'short' letters but written larger than normal). The movement time data plotted against sequence length did not reveal the expected quadratic component, and when writing times were considered for all letter positions and conditions separately it appeared that writing time was only determined by the physical length of the writing trajectory but not by sequence length. It was concluded that neither letters nor strokes consistently predicted reaction and movement times. Instead it was speculated that in handwriting, probably because of the relative slow nature of the task, the specification of motor features was postponed and realized on line with the real time execution of the initial task segments.

In a subsequent study Hulstijn and Van Galen (1988) concentrated on the role of practice and tested whether, at least for handwriting, the unit of programming should be conceived of as having a flexible extent. In this view, the representation of a graphic task within the motor system is highly dependent upon the degree of experience the system has with that particular class of graphemes. Indeed it appeared that the reaction time for novel graphemes was sensitive to the number of compound elements, whereas writing combinations of well-practised capital letters, composed of about the same number of elements was not affected by the same variable. The authors concluded that there is no single answer to the question of processing units in handwriting. On the contrary, it seems that sometimes larger and sometimes smaller chunks of response segments are prepared during reaction time, depending upon the degree of practice a subjects has with the task. A similar conclusion was reached in a study by Portier et al. (1990) who examined the movement time and dysfluency of consecutive segments of novel graphemes as a function of practice. The authors hypothesized that during the initial phase of the acquisition of a novel grapheme the pattern is planned and executed stroke by stroke. When training proceeds, subjects form an internal code which specifies longer and longer substructures of the graphic pattern. The character of the internal code was assumed to be of an abstract nature, comparable to motor programs for allographic instances of letters. From this interpretation of the learning process it follows that, with practice, the production of the first segment of a grapheme will become more and more loaded by concurrent demands on processing resources, due to the increased 'unpacking' load of longer and longer stroke sequences. As predicted, the results showed that the time needed to complete the first stroke of such novel graphemes increased during the successive training sessions relative to the writing time of trajectories at second and third segment positions. This effect was stronger for graphemes, built up of the stroking patterns of a well-known character. The latter finding corroborates the view that greater chunks are more easily assembled from already settled motoric structures.

The experiments reviewed until now suggest that, for handwriting tasks, the subprogram-retrieval model does not fit the data. In none of the experiments a consistent effect of sequence length on reaction time and movement time could be demonstrated. Reaction time, indeed, increased with response length, but the effect was greatly modified by the linguistic, motoric and training status of the sequences used, which seems in contradiction to the notion of a fixed unit of processing. Furthermore, it appeared that writing time per symbol did not increase with sequence length. However, when, together with sequence length, lexical regularity or response compatibility was varied, it appeared that the time to initiate and write separate symbols was affected strongly by these cognitive and motor factors. Hulstijn and Van Galen proposed that the preparation of handwriting is not a unitary process. Instead, one might assume that the programming of a written message proceeds along different independent steps. During the earlier phases of the preparation process rather abstract dimensions like the lexical and phonological structure of a word are encoded and stored in a transient buffer. Storing strategy, size of stored units, decay and search characteristics are typical for the level involved. Later, and concurrent with the real-time execution of the task, spatial and temporal features of the task are specified. This picture is in agreement with the hierarchical tree-traversal model of Rosenbaum et al. (1984; 1987) for key stroking tasks, and Harrington and Haaland's (1987) description of the production of gestures.

Independent processes in handwriting

In this section I will consider evidence on the independence of processes involved in the production of handwriting movements. In this context it is an often cited observation (Merton 1972) that writing patterns of an individual, produced on either a paper note or on a blackboard are highly similar in appearance, even though the musculature and forces involved may widely vary. For several studies this observation formed a starting point to search for the independence of form, scale and anatomical factors in handwriting. Van Galen and Teulings (1983) varied novelty of a writing pattern, the overall size, and the musculature to draw the first stroke of the pattern. According to their three-stage theory of motor programming each of these three experimental variables corresponds to a different process. Novelty should relate to access to long-term motor memory which stores abstract representations of motor patterns. Size should be modulated by a parametrization stage, which provides an overall-force parameter to the muscular system, needed to write a pattern at its required size. The activation of the most appropriate motor units to initiate a task was ascribed to a third, muscle initiation process, and was assumed to be dependent on the anatomical constraints in a given task situation. The experiment was designed according to the Additive Factor Methodology of Sternberg (1969), and the results generally proved the independence of variables related to form, scale and anatomy involved in the task. Meulenbroek and Van Galen (1988) replicated these findings with line drawing tasks.

Pick and Teulings (1983) studied whether subjects were able to modify geometrical aspects of their handwriting. It appeared that subjects could easily change the orientation of the writing line, and also could vary the slant of their script, without disruption of other parameters. It was, however, extremely difficult to modify independently *within letters* the size of the horizontal and the vertical component of letter forms. In correspondence to the conclusion reached by Van Galen and Teulings (1983) the authors suggested that size and geometrical orientation of script are probably controlled by different processes.

Size would be a parameter applied to the motor instructions for a letter as a whole, whereas slant and orientation is varied through the relative contribution of wrist and finger musculature in movement execution.

Further evidence for a modular architecture of the production of handwriting comes from neuropsychological studies. Especially in the field of reading and writing, Ellis (1982, 1988) and Ellis and Young (1988) have presented data, from writing errors in normal subjects as well as from so-called double dissociation manifestations in neurological patients, which support the view that separate cognitive and motor processes are involved in the skill of handwriting.

The discrimination between the monitoring of form and scale factors was corroborated by observations made by Margolin and Wing (1983) on the differential effects of brain strokes and Parkinson's disease upon handwriting. Stroke patients were characterized by disturbances of the letter formation process, whereas Parkinsonian patients lost control of the overall size of letters. Ellis (1982, 1988) and Margolin (1984) made clear that, once a graphemic code has been determined, a bifurcation should be assumed between handwriting and other output modes for letter strings. From that point in the processing chain operations specific for handwriting come into play. Ellis called the later operations *peripheral* processes, and reviewed a number of so-called peripheral acquired dysgraphias providing evidence for the discrimination between a stage responsible for the retrieval of allographic motor patterns, another stage to adjust the allographic motor program to the current biophysical context, and a spatial control mode for the monitoring of spatial parameters of the task. Many of the suggestions made by Ellis and by Margolin have been supported by the findings of Caramazza et al. (1986) and by Goodman and Caramazza (1986). Also, several clinical observations are in agreement with experimental findings as reported above (Black et al. 1989; Baxter and Warrington 1986; Kapur and Lawton 1983). Furthermore, it is interesting to note that for typewriting (Gentner 1983; Rumelhart and Norman 1982) and speech (Levelt 1989) analogous, modular models have been proposed.

So far, the empirical evidence seems to suggest some basic elements for a theory of handwriting. Firstly, preparatory processes in handwriting do not use one single unit of processing. Writing tasks are only partially prepared during the latency phase of the response and many of the task demands seemed to find their expression in effects on real-time execution parameters. Furthermore, it was found that the retrieval of form, the implementation of an overall scaling parameter for size, and the recruitment of appropriate motor units were probable candidates for separate processors in a modular architecture of handwriting processes. However, most of the experiments reported so far concentrated on reaction times in speeded writing conditions. In the following section I will summarize a number of experiments that focussed particularly on task demands during real-time execution of more natural writing tasks.

Evidence for concurrent processing in handwriting

Although studies on the real-time characteristics of natural handwriting tasks are relatively scarse, it may be mentioned that motor as well as lexical and semantic task demands have consistently been shown to be related to the dynamics of writing movements. At a more global level, Brown et al. (1988; 1989) demonstrated in a study on the written production of discourse a trading relation between language production and motor control as measured by writing speed and legibility. The authors suggested that formulation, motor execution and output-monitoring processes, although separate processes, run in parallel and draw on a common source of processing capacity.

The availability of digitizer tablets with a high temporal and spatial resolution (Teulings and Maarse 1984) made it possible to analyse the dynamics of the writing process in more detail. The present author and co-workers studied in a number of studies the effects of task demands on the real-time production of script (Van Galen et al. 1986; 1989; Van Galen 1990; Van der Plaats and Van Galen 1990).

The latter studies were designed to investigate to what extent movement time and spatial features of a written trajectory reflect the combined processing demands of writing tasks. In several studies (Van Galen 1980, 1984) it has appeared that task demands manifest themselves as a prolongation of the writing time of a writing segment that *precedes* the segment which actually realizes a particular demand. In one study (Van Galen et al. 1986) the effects of word length, letter position and letter length on reaction times and writing times were analysed. It appeared that the *initiation* of words took 12 ms more for 1 syllable length increase, but once writing had started longer words evidenced a speeding up of the writing process. An analogous finding has been produced by Van der Plaats and Van Galen (1990). Longer words led to a prolongation of the time devoted to the spacing movement between the preceding word and the experimental word, but longer words themselves were written more quickly. The effects were interpreted as evidencing a hierarchical processing strategy. At first, and more remote from the real-time production proper, a phonological code of the task word is set up to guide later writing movements. Because for longer words a more extended phonological code has to be installed the *initiation* of longer words is delayed. Once writing has started this phonological code is translated into its corresponding graphemic codes. The latter process is speeded up when a longer string is met in the phonological buffer. However, when individual writing times for identical letters at varying letter positions were studied it appeared that, independently from the overall speeding up effect, a letter position effect was found. The same letter was writtten more slowly when it occurred at a more initial position in the task word. It was concluded that, after the installation of a phonological code and a speed setting process at word level, a letter by letter grapheme selection process was responsible for the lexical and motor processing at letter level. The increase of writing speed towards the end of a word was attributed to the shrinking content of the phonological buffer which caused a decreasing retrieval load for letters at later positions. In Van Galen et al. (1989) the effect of letter position on writing time has been replicated. In this study also, independent repetition effects at the letter level and the stroke level were shown. Double letters led to a decrease of writing time of the letter that preceded the doubling, which was analogous to the finding of a reduced initiation time for words with a repeating syllable structure (Van Galen 1990). But, the writing of the double letter pair itself was delayed compared to non-repeating letter pairs. The latter finding of a dissociation of a facilitative effect of repetitiveness before the initiation of writing and an inhibitory effect during the writing process has been demonstrated with the repetition of phonologically identical syllables as well. In Van Galen (1990) the combined effects of the phonological structure of a word and the motor complexity of separate letters were studied. Analysis of movement time data in this study showed that, at word level, a global, slowing down of the writing movements was found as a function of the phonological similarity of consecutive syllables of task words, but this effect was independent of a local effect at letter level of a repetitive stroking structure (as in the letter *m*). Again, these findings support a hierarchical processing of information during real-time word production. Before the initiation of writing movements a phonological code is placed into short-term memory. The construction of such a code is less demanding for a phonologically repeating structure as is evidenced by the shorter latencies for words with a repeating syllable structure. During the writing of a word, the retrieval of phonologically similar elements represents the more difficult condition. This effect, however, is additive to a stroke repetition effect at letter level. The latter increase of writing time for comparable segments of *m* compared to *n* was attributed to the non-shrinking feature of the motor buffer.

The analysis of real-time writing processes has produced several elements for a further specification of a psychomotor model of handwriting. Most importantly, handwriting has been shown to be a typical *parallel* task. There was ample evidence that demands of differing nature have summed effects on writing trajectories. At the same time, however, a specific hierarchy of the manifestation of task demands has been demonstrated. Effects related to greater task units (e.g. words) affected the production speed of earlier and thus relative to the real-time realization of the demand more remote task segments. At an intermediate, letter level, repetition and letter length influenced writing trajectories two or one letter position ahead of the demanding structure. At the smallest level which was studied, the letter stroke, it appeared that repetitions and difficult stroke alterations (Van Galen et al. 1986) led to an increase of writing time of the difficult strokes proper. Presumably, for the latter task elements movement organization and real-time production coincide.

Contours of a model of handwriting

Although it might be too early to propose a realistic description of handwriting, I have tried to sketch a psychomotor model of the task. It should be stressed that the model is based on few empirical data. Certainly the model is not a quantitative description, although quantitative measures on several stages are available. Presuppositions to this model, as derived from the review of three research questions in the preceding sections may be summarized as follows:

(1) Handwriting is the outcome of several different processing modules, each of which addresses a specific feature of the message.

(2) The architecture of these modules is hierarchical in the sense that output from each stage forms the input for the next lower stage.
(3) From the the top to the lower stages of the hierarchy processing units decrease in size.
(4) All modules are engaged in processing activities concurrently. However, higher modules are further ahead to real-time output than lower modules.
(5) To accomodate for time frictions between modules storage buffers allow the transient buffering of stage output.

A visual description of the model is presented in fig. 1. There, I have listed the component processes as suggested by the experiments reported above and by the neuropsychological work of Ellis (1982, 1988). In the left column of the figure separate processing modules are indicated for which an independent status seems to be justified. The vertical organization of the modules corresponds to their assumed hierarchical ordering relative to real-time realization of a written message. Arrows between neighbour stages express that output from higher stages forms the input for the next lower stage.

In the right column of fig. 1 the mediating role of storage buffers is indicated. In the model it is assumed that the output from each stage is transiently stored in working memories which are typical for the corresponding stage. The role of these temporal storage nodes is twofold. Firstly, they accommodate for time frictions between information processing activities in different modules. Secondly, I assume that a processor lower in the hierarchy can read information from the buffer with a unit size which is appropriate for that stage.

It is not necessary to assume that storage buffers, which essentially have a role as working memories, form separate structures, independent from the processing module to which they relate. Dell (1986), who developed a model for the generation of spoken utterances, provided evidence that at each level of his model the representation of an utterance may be conceived of as a set of 'tagged nodes' with a specific activation spreading characteristic which is related to the transient status of the information at that level.

In the middle column of the model we have identified the hypothetical nature of the unit sizes which each stage uses in importing information from the next higher stage.

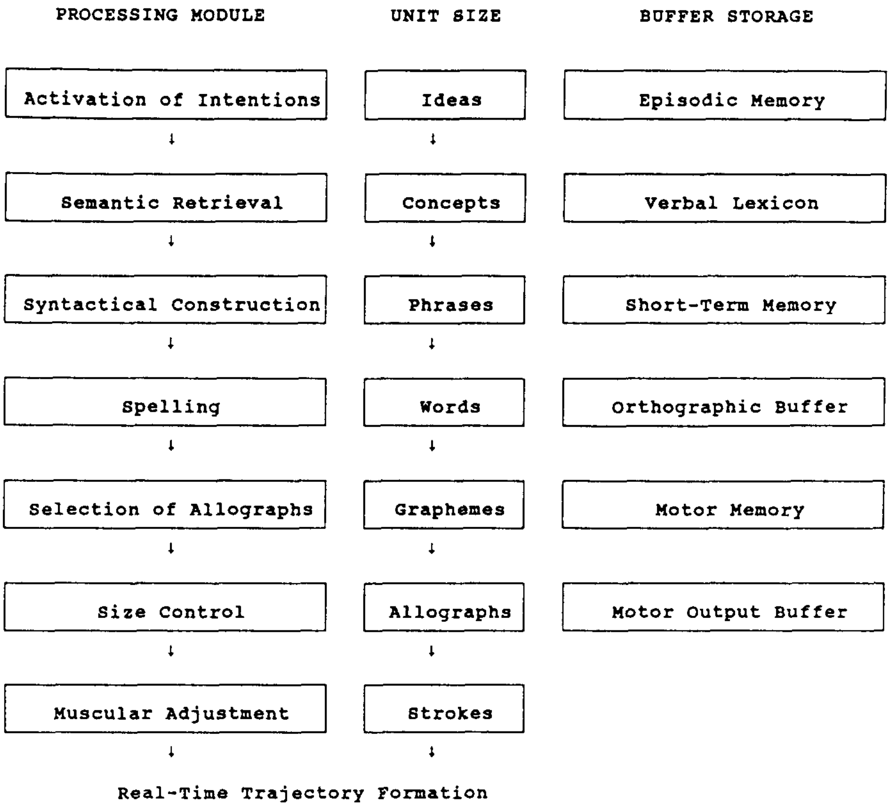

Fig. 1. Architecture of processing modules, processing units and mediating memory stores for the production of handwriting. In the left-hand column the hierarchy of processing modules is indicated. The central column describes the identity of the processing units addressed in the corresponding module. The right-hand column refers to the storage nodes that mediate in the communication between successive levels of the model.

It should be said that the number of different processing modules should not be considered to be a unique solution for current empirical data. We borrowed the highest three, most abstract processors from psycholinguistic literature. There, it is commonly believed that intentions, semantic structures and syntactical processes form psychologically separate categories (Levelt 1989). A further differentiation, however, is possible. Writing comes into the focus of our model with the spelling module. Spelling is the process through which elements of an utterance are substituted by their corresponding graphemic codes. In handwriting literature it is commonly held that humans have two different routes for the activation of a graphemic representation of a word. One process makes use of phoneme-to-grapheme conversion rules. Through the other, lexical route people should have direct access to stored knowledge about the spelling of written words. The reliance on one or on the other of both routes is thought to be dependent on the type of words to be spelled (words or non-words) and on the regularity of the spelling habits of a specific language. Evidence for strict versions of the dual-route theory was mainly derived from clinical studies of neurological patients with spelling difficulties (Margolin 1984; Ellis 1982), and from studies on reading. In the latter research area, the independence of both routes has been questioned (Humphreys and Evett 1985). We have, therefore, and for reasons of simplicity, chosen for an undifferentiated spelling module.

Motor processes play a role in the model below the spelling module. From this level the model discriminates between selection of allographs, size control and muscular adjustment. The selection of allographs should be seen as the activation of motor programs or engrams corresponding to the graphemic representation in the orthographic buffer and to the instructed writing mode (lower case, upper case, block letters, script letters, etc). In essence, the selection of an allographic motor pattern is a two-step process. The current writing mode (e.g. cursive script) activates the long-term motor repertoire that should be applied in the second, grapheme-to-allograph conversion step. Evidence for a distinct status of repertoires for upper-case and lower-case forms of letters has recently been produced in a clinical study by Patterson and Wing (1989). The model does not follow a suggestion of Ellis (1982) who differentiates between an allograph level and a graphic motor pattern processor. As pointed out in the section on elementary facts on handwriting, I assume that letter forms, and thus allographs, are stored and retrieved as spatial codes for the guidance of writing movements. Although actually further variations of letter forms arise as a result of biophysical influences on the generation of the real-time writing trajectory, I do not think that these graphic motor patterns are stored in long-term memory. More probably, such variations are, together with actual trajectories of letter connection strokes, emergent features of the writing process.

Writing size (and speed) is proposed to be monitored in a separate stage. Size control, in the model, is linked to the letter level and not to separate letter strokes. This proposition is based on the finding of Pick and Teulings (1983) that size manipulations in writing tasks are difficult to apply at a smaller than letter level. The final stage as described by the model is thought to represent the recruitment of synergies of agonist and antagonist muscle forces necessary for the realization of a writing trajectory in a given biophysical context. This stage represents one of the most intriguing features of the motor system. We saw that motor equivalence is a very explicit trait of the handwriting process. A simple observation of the writing hand shows that the actual employment of the muscular apparatus is heavily dependent on the place in the working field where letters are written. Reaction time studies wherein wrist and finger movements were differentially used lend support to the idea of an independent muscular recruitment process. Recent studies in the field of simple movements have made clear that the details of muscular control are far from simple (Gottlieb et al. 1989). At this level of the model strokes are suggested as being the most probable units of processing.

A further feature of the handwriting model as depicted in fig. 1 is the hierarchical organization of the modules. From the experiments on task demands during task execution it was concluded that higher processors operate at longer distance (in time) from real-time execution. Although this type of hierarchy might be considered as indicative of the serial architecture of the model, it must be stressed that, from a functional point of view, the model has a parallel character. This is possible because processors higher in the hierarchy, continue to process information related to forthcoming parts of the message simultaneously with the spelling out of the details of the current output segments by the lower order processors.

A serious limitation of the model in its present form is that it does not represent any feedback process. In a number of studies it has been made clear that handwriting is severely delayed and often disturbed when visual feedback is prohibited (Smyth and Silvers 1987). Functions of visual control have been related to the overall control of word and letter order, as well as to the retrieval of separate letter strokes from the motor output buffer (Van Galen et al. 1989). It should be remembered, however, that the model is designed to give a description of the generation of script. Afferent control seems a natural but not strictly necessary condition.

Concluding remarks

Early in the present article the assumption was made that stroke generation and letter formation should not be seen as biophysical processes only. Indeed, cognitive variables such as linguistic and lexical complexity, word and letter length, and other contextual factors significantly interfered in real-time stroke production. Mainly on the basis of these findings a functional architecture of handwriting was designed. However, it must be stated again that the model gives the present 'state of the art' only. It is based on limited evidence and it is limited in its scope. There is certainly a need to verify the elementary findings in further studies.

Another shortcoming of the present model is that it does not specify how load effects related to cognitive task demands operate so as to prolong trajectory formation processes. Although it is often done, it is not a satisfactory explanation to refer to the concept of limited resources. The question then is how psychological load causes the increases of movement time as consistently found. A possible mechanism that may explain load effects has been suggested by the present author (Van Galen et al. 1990) in a paper on the application of power spectral density analysis in research on drawing and writing movements. In this paper it was shown that the relative energy in bands of the frequency spectrum derived from the acceleration profiles of repetitive wrist and finger movements was affected by demands related to forthcoming movement segments. It was proposed that in a more complex task situation the physiological signal related to the recruitment of muscle force is contaminated with neuromotor noise, leading to a less efficient recruitment process in the muscle system.

Other important areas of research have also been underexposed. This is specifically true for developmental research in the field of handwriting. In recent years we have seen a strong upsurge of developmental studies as this field was strongly influenced by the process-oriented wave in the field of motor studies. Also in this area fast sampling techniques made it possible to detect basic features of the development of movement dynamics in children (see e.g. Meulenbroek and Van Galen 1986; Wann 1987) and of motor disturbances related to mental retardation (Wann and Jones 1986). Especially interesting is the detection of the role of action grammars (Thomassen et al., this issue) and their development (Goodnow and Levine 1973). At present, the role of such grammars, which seem to indicate a priori probabilities of action alternatives, is insufficiently explained by current modular models. It might be that the rules of these grammars can be understood as reflecting activation states in memory nodes that are related to learned or ecologically prevalent action alternatives.

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