Acta Psychologica 82 (1993) 353–365
North-Holland

Effects of lexicality and trigram frequency on handwriting production in children and adults

Pascal Zesiger, Pierre Mounoud and Claude-Alain Hauert *

University of Geneva, Geneva, Switzerland

Recent studies of handwriting have shown that linguistic variables, such as phonology or lexicality, influence various aspects of the production of letter sequences. Following a previous experiment, in which a facilitation effect of words over pseudowords has been documented both in children and in adults, an experiment is reported concerning the effect of lexicality and of trigram frequency on handwriting production at different levels of handwriting mastery. In this experiment, 8- to 12-year-old children and adults were asked to write words, pseudowords ending with a frequent trigram, and pseudowords ending with a nonfrequent trigram. Results show that in adults there is a facilitation effect of words over pseudowords and of frequent trigrams over nonfrequent trigrams. In children, no clear effect of lexicality or trigram frequency could be observed. Developmental trends show that major changes in children's handwriting occur between 8 and 10 years, whereas only minor modifications are observed between 10 and 12 years.

Handwriting is a complex perceptuo-motor skill which differs from other graphomotor tasks, such as drawing or scribbling, in various ways. One of the most obvious differences is of course the involvement of the linguistic system which seems to influence diverse aspects of handwriting production. Thus, Wing (1980) showed that syllabic stress influences letter size variations in English. Likewise, in Dutch, Van Galen (1990) documented a facilitation effect of phonological

Correspondence to: Pascal Zesiger, FAPSE, University of Geneva, 9, route de Drize, 1227 Carouge, Switzerland. E-mail: zesiger@cgeugel1.bitnet

* The authors wish to thank Maryse Badan, Martine Holzer, Giovanni Lepori, Fabienne Manganiello and Denis Page for their help in the data acquisition and Mathias Durrenberger for computing acquisition and data processing programs. We also wish to express our gratitude to the teachers and the pupils of the Genevan Public Schools and to the adult subjects who participated in the experiments.

similarity on motor response initiation, but an inhibitory effect of the same factor on movement time. Portier et al. (this volume) showed evidence of a lexical effect (words versus pseudowords) in shorthand production; they did not however observe such an effect in latin script production. Finally, Orliaguet and Boë (this volume) reported a linguistic effect related to the application of a grammatical rule in the production of homographic and homophonic French words. Indeed, these are only but a few of the possible linguistic factors affecting handwriting movements.

In addition to these 'higher level' variables, some local sources of variation have been investigated. Several authors reported contextual effects related to surrounding letters. For instance, Thomassen and Schomaker (1986) showed that the duration and size of a letter are influenced by the next letter (anticipation effect) and, although to a minor extent, by the preceding one (aftereffect). Orliaguet and Boë (1990) further quantified this anticipation phenomenon by demonstrating that, in the production of bigrams such as 'll' versus 'ln', the downstroke of the letter 'l' is clearly affected by the next letter, whereas the preceding upstroke remains invariant. By contrast, the aftereffect, studied in the production of 'll' versus 'nl', seems to influence both the up- and the downstrokes of the letter 'l'.

In these respects, the first goal of the present studies is to investigate further the sources of variation which are specific to letter sequences writing. More particularly, we are addressing the issue of lexical (words versus pseudowords) and letter frequency (trigrams) influences on handwriting production. These aspects are investigated at different stages of handwriting acquisition, that is to say in children and in adults.

Handwriting in children has been studied by numerous authors using a large variety of tasks and measures, ranging from qualitative evaluation of the production to detailed analyses of the movement kinematic and dynamic properties. Given these differences, it is hardly surprising that these studies lead to partially contradictory results. One of the main themes of disagreement is related to developmental patterns of the various measures with age. Some authors reported gradually developing capacities, in particular in terms of handwriting speed, measured by the number of letters produced per minute (Bang 1959; Ziviani 1984). Others showed evidence of discontinuities in this development involving a temporary decline of the performance on indexes such as movement velocity, i.e. trajectory length divided by movement duration, and movement fluency (Meulenbroek and Van Galen 1986, 1988). Others yet described evolutions characterized by dramatic changes between 7–8 and 10 years and by a stabilization of the performance thereafter (Mojet 1991).

Despite the important amount of research concerning handwriting development, it remains that only a few studies using modern technology have focussed on analyzing the production of words or word-like material. Thus, the second goal of our research is to provide further data on the development of several kinematic indexes related to handwriting processes in elementary school children.

In a previous experiment (Zesiger et al. 1990; in prep.), 40 right-handed girls aged 8, 9, 10, 11 and 12 years and 8 right-handed, adult females were asked to write four 6-letter French words paired with four pseudowords; each pair of stimuli began with the same trigram. The productions were recorded by means of a digitizing tablet. Various measures were computed on the first trigram: duration, trajectory length, average velocity and dysfluency, i.e. the number of extrema in the velocity pattern.

The results showed a significant advantage of words over pseudowords on the average velocity in adults: as can be seen in table 1, the average velocity was higher in the first trigrams inserted in words than in the ones inserted in pseudowords. In children, we also observed a lexical effect on duration for three out of four trigrams: table 1 indicates that the movement time for writing the first trigram is shorter in words than in pseudowords. However, one trigram (ALC) had an opposite tendency.

Table 1
Lexical effect observed in adults and children.

Initial trigram	Adults		Children	
	Average velocity (cm/s)		Duration (s)	
	Word	Nonword	Word	Nonword
CLA	3.841	3.704	1.833	1.854
MAR	2.851	2.789	2.303	2.406
ALC	3.559	3.435	1.852	1.782
RAM	2.790	2.725	2.060	2.114

This last result has been tentatively interpreted as proceeding from the fact that the final trigram of the word ('alc*ool*') was very rare in French, and consequently that children displayed an anticipation effect related to the frequency of the last trigram.

As far as developmental trends were concerned, some indexes exhibited complex patterns of evolution with age suggesting the presence of qualitative differences in the preparation and execution of handwriting movements in children.

Given the results obtained in this experiment, we designed a new experiment whose goals were (1) to replicate the lexical effect with controlled stimuli as far as the frequency of the last trigram is concerned, (2) to verify the existence of a trigram frequency effect, and (3) to get additional data on the development of the various indexes with age with a somewhat larger subject sample.

Method

Subjects

Sixty right-handed girls attending public Genevan schools split into 5 age groups (8, 9, 10, 11 and 12 years, ± three months from their date of birthday) and 12 right-handed, female students (mean age = 25 years) participated in the experiment.

Material

The productions were recorded by means of a digitizing tablet Summagraphics Microgrid 1724H (spatial accuracy = 0.127 mm, sampling rate = 170 Hz) monitored by a PC. The writing device was a slightly thicker than regular ballpen attached to the tablet through a flexible wire.

Stimuli

The stimuli consisted of four trigrams inserted in three different contexts: first trigrams of 6-letter French words ('*cab*ane', '*cal*cul', '*esp*ace' and '*nom*bre'), first trigrams of 6-letter pseudowords ending with a frequent trigram ('*cab*ure', '*cal*par', '*esp*ore', '*nom*ple'), and first trigrams of pseudowords ending with a nonfrequent trigram ('*cab*ode', '*cal*mec', '*esp*uge', '*nom*gre'). Two words were matched with frequent final trigram pseudowords, and the other two were matched with nonfrequent final trigram pseudowords. The trigram frequency was established by computing the log value of the total textual trigram frequency based on statistical data on the orthographic structure of the French language (Content and Radeau 1988). The stimuli were written in lower-case, cursive letters (copied from the handwriting standards for Genevan schools) on 15 × 10 cm white pieces of cardboard.

Procedure

The experimenter instructed the subject that she was to write down visually presented words and meaningless letter sequences using her usual handwriting in unstressed situations. The subject was presented with the first stimulus and asked to read it aloud. The stimulus card was then removed in order to avoid copying strategies and the subject was asked to write it down. Before each trial, the experimenter called the subject's attention and 500 to 1000 ms after, an auditive signal was delivered by the PC indicating the beginning of the acquisition period to the subject. After the subject finished her production, the experimenter ended the acquisition period, which was notified with a second auditive signal. If the stimulus was correctly spelled, the next stimulus was presented. Once the 12 stimuli were produced, a new set of trials started with stimulus 1. The presentation order of the stimuli was pseudorandomly varied across the 12 subjects of an age group. Children wrote 5 times the 12 stimuli during a first session, and again 5 times during a second session which took place within the next 1 or 2 days. Adults wrote 10 times the whole set of 12 stimuli during the same session. Only the final eight recordings have been selected for analyses, the first two being considered as a familiarization period.

Data processing and analyses

The handwriting samples were filtered with a low-pass, Finite Impulse Response filter (Rabiner and Gold 1975) with a 9 Hz cut-off frequency. The resulting trajectory and absolute velocity pattern were displayed on a monitor and the first trigram (last stroke excepted so as to avoid a bias due to a contextual anticipation effect related to the next letter) was isolated with a semi-automatic procedure. The following indexes were computed on the first trigram: duration, trajectory length, average velocity and dysfluency.

Separate MANOVAs were performed for adults and children. The first analyses aimed at determining whether the subjects' performance was influenced by the *lexical* variable (within-subject factors Lexicality [2] and Trigram [4], between-subject factor Age [5] for analyses computed with children); the second analyses aimed at investigating the effect of the *final trigram frequency* variable (within-subject factors Frequency [2] and Trigram [4], between-subject factor Age [5] for analyses concerning children).

Results

Adults

The results obtained with adults are described in table 2. At the *lexical* level, a main effect of words over pseudowords can be observed on duration and on trajectory

Table 2
Adults' results.

Variable	Effect	*df*	*F*	*p*
Lexicality				
Duration	Lexicality	1,11	7.09	< 0.025
	Trigram	3,9	43.84	< 0.001
Length	Lexicality	1,11	7.70	< 0.02
	Trigram	3,33	26.79	< 0.001
Av. vel.	Trigram	3,33	27.79	< 0.001
	Lex×Tri	3,33	9.18	< 0.001
Dysfl.	Trigram	3,33	128.19	< 0.001
Frequency				
Duration	Frequency	1,11	4.93	< 0.05
	Trigram	3,9	65.53	< 0.001
Length	Frequency	1,11	8.41	< 0.015
	Trigram	3,9	27.37	< 0.001
Av. vel.	Trigram	3,33	25.19	< 0.001
Dysfl.	Trigram	3,9	142.68	< 0.001

length (table 3): the first trigrams belonging to words are written with a shorter duration and trajectory length than the matched trigrams inserted in pseudowords. No main effect of lexicality appears on the average velocity, but there is an interaction between Lexicality and Trigram. Table 3 shows that there is an advantage of words (higher velocity) over pseudowords for three out of four trigrams and a reverse pattern for one trigram. In this instance, it seems plausible that the similarity of structure between the first trigram (CAL) and the last one (CUL) played an inhibitory role on the first trigram production, as shown by Van Galen (1990). Finally, dysfluency does not appear to be affected by the lexical variable.

Concerning the *Final Trigram Frequency*, the frequency effect reaches significance both on duration and on trajectory length (table 4), indicating a longer movement

Table 3
Lexical effect in adults.

	Duration (s)		Trajectory length (cm)		Average velocity (cm/s)	
	Word	Nonword	Word	Nonword	Word	Nonword
CAB	0.845	0.866	2.962	3.020	3.571	3.563
CAL	0.742	0.734	2.501	2.573	3.453	3.578
ESP	0.932	0.955	3.428	3.472	3.756	3.706
NOM	1.148	1.156	3.338	3.325	2.937	2.917

Table 4
Trigram frequency effect in adults.

	Duration (s)		Trajectory length (cm)	
	Freq.	Nonfreq.	Freq.	Nonfreq.
CAB	0.859	0.866	2.969	3.020
CAL	0.724	0.734	2.491	2.573
ESP	0.955	0.961	3.472	3.454
NOM	1.156	1.164	3.325	3.351

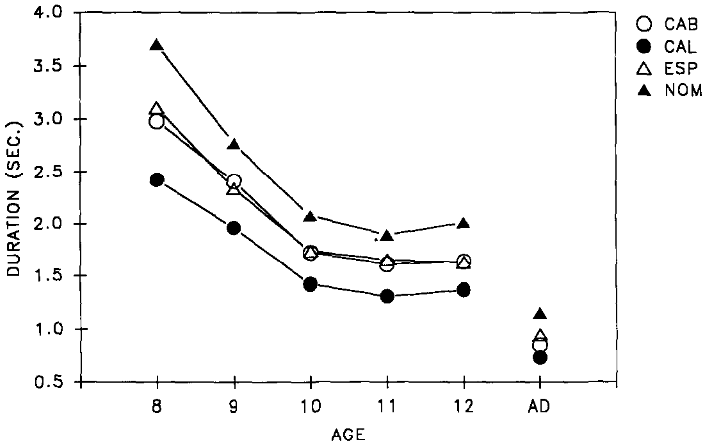

Fig. 1. Duration of the first trigrams by age.

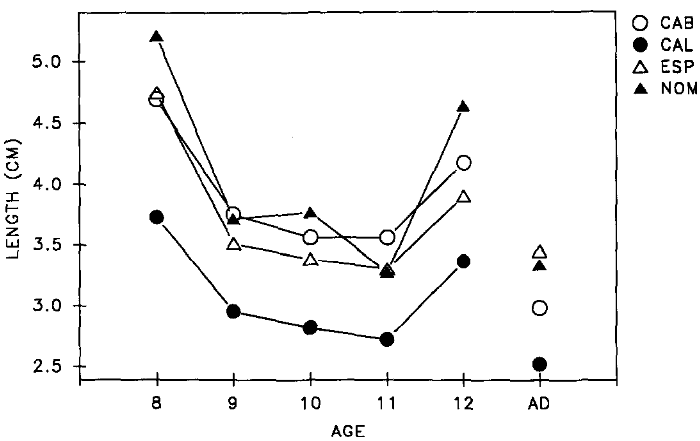

Fig. 2. Trajectory length of the first trigrams by age.

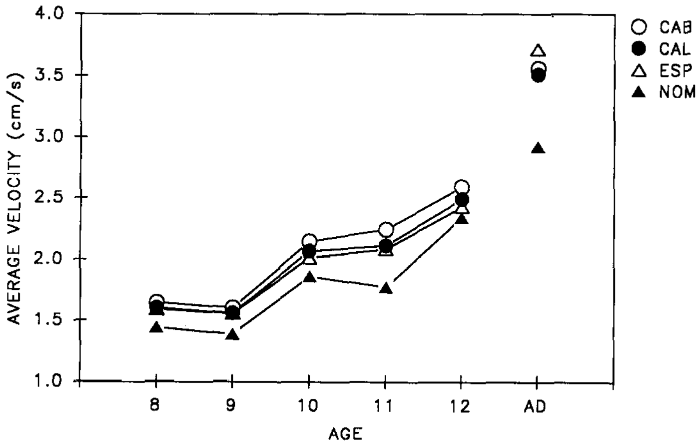

Fig. 3. Average velocity of the first trigrams by age.

time (respectively length) on the first trigram of pseudowords ending with a nonfrequent trigram than on pseudowords ending with a frequent trigram.

Children

Children's results are displayed in table 5. These results show that there is no main effect of lexicality on any index. There is nevertheless a significant interaction of the factors Lexicality and Trigram both on trajectory length and on average velocity.

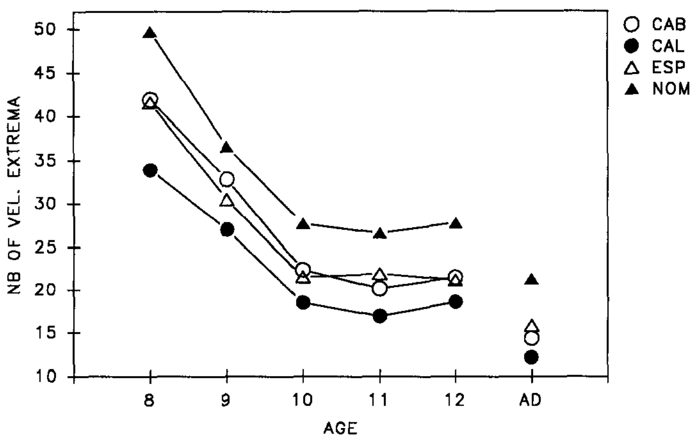

Fig. 4. Dysfluency of the first trigrams by age.

Table 5
Children's results.

Variable	Factor	df	F	p
Lexicality				
Duration	Age	4,55	38.76	< 0.001
	Trigram	3,53	406.72	< 0.001
	Age × Tri	12,165	5.74	< 0.001
Length	Age	4,55	4.44	< 0.005
	Trigram	3,53	227.09	< 0.001
	Age × Tri	12,165	3.33	< 0.001
	Lex × Tri	3,165	5.05	< 0.003
Av. vel.	Age	4,55	6.32	< 0.001
	Trigram	3,53	48.69	< 0.001
	Age × Tri	12,165	1.98	< 0.03
	Lex × Tri	3,53	6.34	< 0.001
Dysfl.	Age	4,55	21.64	< 0.001
	Trigram	3,53	218.34	< 0.001
	Age × Tri	12,165	4.38	< 0.001
Frequency				
Duration	Age	4,55	41.22	< 0.001
	Trigram	3,53	310.04	< 0.001
	Age × Tri	12,165	4.79	< 0.001
Length	Age	4,55	4.59	< 0.005
	Trigram	3,53	216.96	< 0.001
	Age × Tri	12,165	3.20	< 0.001
Av. vel.	Age	4,55	6.72	< 0.001
	Trigram	3,53	47.93	< 0.001
	Age × Tri	12,165	1.98	< 0.03
Dysfl.	Age	4,55	22.20	< 0.001
	Age × Freq	4,55	2.86	< 0.04
	Trigram	3,53	181.75	< 0.001
	Age × Tri	12,165	3.87	< 0.001
Context				
Duration	Age	4,55	40.36	< 0.001
	Context	2,110	4.32	< 0.02
	Trigram	3,53	384.14	< 0.001
	Age × Tri	12,165	5.57	< 0.001
Length	Age	4,55	4.48	< 0.005
	Context	2,110	4.35	< 0.02
	Trigram	3,53	234.65	< 0.001
	Age × Tri	12,165	3.29	< 0.001
	Cont × Tri	6,50	5.54	< 0.001
Av. vel.	Age	4,55	6.58	< 0.001
	Trigram	3,53	57.69	< 0.001
	Age × Tri	12,165	2.24	< 0.015
	Cont × Tri	6,50	3.50	< 0.01
Dysfl.	Age	4,55	21.32	< 0.001
	Age × Cont	8,110	2.10	< 0.05
	Trigram	3,53	224.72	< 0.001
	Age × Tri	12,165	4.51	< 0.001

However, the patterns observed do not seem to make much sense, as the trigrams evolve in different directions in each case.

The results obtained on the last trigram frequency do not reveal a significant main effect of this factor on the children's performance either. The only relevant result in this respect is a significant interaction between Age and Frequency on dysfluency, which indicates that children aged 10 and 11 years tend to display a frequency effect on this index.

Further MANOVAs were computed concerning the effect of lexicality and last trigram frequency on all indexes separately for each age group. These analyses did not show evidence of clear effects of either lexicality or final trigram frequency at any age.

Given the fact that the differences due to lexicality and trigram frequency observed in these analyses are small or nonexistent in children, the age trends were investigated by computing additional MANOVAs including all the data (within-subject factors Context [3] and Trigram [4], between-subject factor Age [5]). As can be seen in table 5, both the Age and the Trigram factors are significant on all indexes. The interaction between Age and Trigram is also significant in all instances, which indicates that the different trigrams do not exactly evolve in the same manner with age. As far as duration is concerned (fig. 1), there are significant differences between 8- and 9-, and between 9- and 10-year-olds; overall, both linear and quadratic trends reach significance. Trajectory length develops quite differently (fig. 2): it is significantly longer in 8-year-old subjects than in 9-year-olds; it remains rather stable between 9 and 11 years, and then increases again at 12 years (quadratic trend). The average velocity (fig. 3) significantly augments between 9- and 10-year-olds; the difference between 11- and 12-year-olds almost reaches significance ($p < 0.06$). Globally, only the linear term is significant. Dysfluency develops according to the same profile as duration (significant linear and quadratic trends): it decreases between 8 and 10 years, and changes only little after that age (fig. 4). Finally, it is interesting to note that, even though children do not display clear evidence of lexicality and trigram frequency effects, they do discriminate the different contexts on several indexes, namely duration and trajectory length.

Discussion

The results obtained with adult subjects in the two experiments show that there is an effect of word writing over pseudoword writing, which is expressed through indexes such as movement duration, trajectory length and average velocity. Furthermore, another effect related to the frequency of the last trigram also appears on measures computed on the first trigram in 6-letter pseudowords.

The origin of these effects within the models developed in the last few years for spelling and writing in the field of cognitive (neuro)psychology remains an open question. Given the procedure used in this experiment, i.e. a visual presentation of the stimuli, an explanation of the lexical effect based on the use of different routes, usually referred to as 'lexical' (or 'addressed') and 'phonological' (or 'assembled') orthographies (Ellis 1982; Goodman and Caramazza 1986; Shallice 1988), is hardly tenable. It would imply in particular that subjects, when reading the stimulus, access (for words) or compute (for non-words) a phonological representation which they recode into a graphemic representation only when instructed to start writing. Moreover, such an interpretation would hold to account for movement latency (not measured in our experiment), but it does not give us a clue about the reason why these effects affect movement duration and trajectory length. Consequently, two alternative (and eventually complementary) hypotheses based on mechanisms located much lower in the hierarchy of representations could be put forward.

A first interpretation considers that these effects are due to changes in the processing load. As suggested by Van Galen (1991, in press), within a limited processing resource system, '... increase of demands upon any of the modules leads to deterioration and slowing down of processing in other modules'. The second one implies that movement production in handwriting is simultaneously controlled by feedforward and feedback mechanisms. Feedback mechanisms would be important for checking whether the actual production corresponds to the action plan and would essentially function as an error detection device. Now, it may be that the need for on-line monitoring of the production is inversely proportional to the familiarity of the sequence to be produced. In this respect, such a hypothesis accounts for the fact that changes are observed throughout the production.

The present data emphasize the high degree of complexity of the processes involved in preparing and executing handwriting movements. More particularly, they demonstrate that the production system is sensitive to subtle differences in the structure of the sequences of letters that it processes. Our research shows that this system is sensitive to the frequency of the final trigram, but this phenomenon could eventually be extended to single letter or bigram frequency.

Concerning these effects, the situation is less clear for children. In the first experiment, children displayed a lexical effect for three out of four trigrams. Given our interpretation of the paradoxical effect observed with one trigram, we would have expected children to show evidence of a lexical effect as well as a last trigram frequency effect in the second experiment, at least in the oldest age groups. Since none of them proved true, our first interpretation needs to be reconsidered.

The first thing to be noted is that in adults the differences between conditions are small and may only reveal themselves in subjects performing the task with a very low variability, which is not the case in children. Secondly, the post-hoc hypothesis we put forward after the first experiment (presence of a last trigram frequency effect in children) may be true only for rather extreme values. Indeed, the final trigram frequency was clearly contrasted between the frequent and the nonfrequent conditions, but on the whole we did not select extremely rare trigrams in French such as the one appearing in the word 'alcool'. Alternatively, it may be that the inhibitory effect of the word 'alcool' compared with 'alcano' is related to the repetition of the letter 'o' rather than to the frequency of the trigram per se. Finally, it should be noted that a final trigram frequency effect can only be observed on measures computed on the first trigram if subjects program their activity a few letters in advance, which again may not be the case in children. According to the developmental literature, children use a more piece-meal strategy in handwriting production than adults do: they would program their movements stroke by stroke and would gradually integrate these units into a more global action plan (Thomassen and Teulings 1983).

Concerning developmental trends, our results seem to confirm those obtained by Mojet (1991), with considerable changes between 8 and 10 years, and seemingly minor modifications afterwards. However, the important increase of length observed in the 12-year-old group could suggest a change in the control strategy at this age. Additionally, it should be noted that there still is a large gap between the performance of the oldest children (11- and 12-year-olds) and that of our group of adult subjects. This may be taken as an indication that handwriting still considerably changes over the period of adolescence, about which further research is clearly needed.

References

Bang, V., 1959. Evolution de l'écriture de l'enfant à l'adulte [Evolution of handwriting from childhood to adulthood]. Neuchâtel: Delachaux and Niestlé.

Content, A. and M. Radeau, 1988. Statistical data on the orthographic structure of French. European Bulletin of Cognitive Psychology Special Issue, September.

Ellis, A.W., 1982. 'Spelling and writing (and reading and speaking)'. In: A.W. Ellis (ed.), Normality and pathology in cognitive functions (pp. 113–146). London: Academic Press.
Goodman, R.A. and A. Caramazza, 1986. Aspects of the spelling process: Evidence from a case of acquired dysgraphia. Language and Cognitive Processes 1, 263–296.
Meulenbroek, R.G.J. and G.P. van Galen, 1986. 'Movement analysis of repetitive writing behaviour of first, second and third-grade primary school children'. In: H.S.R. Kao, G.P. van Galen and R. Hoosain (eds.), Graphonomics: Contemporary research in handwriting (pp. 71–92). Amsterdam: North-Holland.
Meulenbroek, R.G.J. and G.P. van Galen, 1988. 'The acquisition of skilled handwriting: Discontinuous trends in kinematic variables'. In: A.M. Cooley and J.R. Beech (eds.), Cognition and action in skilled behavior (pp. 273–281). Amsterdam: North-Holland.
Mojet, J.W., 1991. 'Characteristics of the developing handwriting skill in elementary education'. In: J. Wann, A.M. Wing and N. Sovik (eds.), The development of graphic skills (pp. 53–75). London: Academic Press.
Orliaguet, J.P. and J.L. Boë, 1990. 'Régulation temporelle des mouvements d'écriture en fonction des contraintes spatiales' [Temporal regulation of handwriting movements as a function of spatial constraints]. In: V. Nougier and J.P. Blanchi (eds.), Pratiques sportives et modélisation du geste (pp. 163–177). Grenoble: Grenoble Sciences.
Orliaguet, J.-P. and L.-J. Boë, 1993. The role of linguistics in the speed of handwriting movements: Effects of spelling uncertainty. Acta Psychologica 82, 103–113 (this volume).
Portier, S.J., G.P. van Galen and A.J.W.M. Thomassen, 1993. Phonological and orthographic demands in the production of handwriting. Acta Psychologica 82, 251–274 (this volume).
Rabiner, L.R. and B. Gold, 1975. Theory and application of digital signal processing. Englewood Cliffs, NJ: Prentice-Hall.
Shallice, T., 1988. From neuropsychology to mental structures. Cambridge: Cambridge University Press.
Thomassen, A.J.W.M. and L.R.B. Schomaker, 1986. 'Between-letter context effects in handwriting trajectories'. In: H.S.R. Kao, G.P. van Galen and R. Hoosain (eds.), Graphonomics: Contemporary research in handwriting (pp. 225–238). Amsterdam: North-Holland.
Thomassen, A.J.W.M. and H.L.M. Teulings, 1983. 'The development of handwriting'. In: M. Martlew (ed.), The psychology of written language (pp. 179–213). New York: Wiley.
Van Galen, G.P., 1990. Phonological and motoric demands in handwriting: Evidence for discrete transmission of information. Acta Psychologica 74, 259–275.
Van Galen, G.P., 1991. Handwriting: Issues for a psychomotor theory. Human Movement Science 10, 165–191.
Van Galen, G.P., in press. 'Handwriting: A developmental perspective'. In: A. Kalverboer, B. Hopkins and R. Geuze (eds.), Motor development in early and later childhood. Cambridge: Cambridge University Press.
Wing, A.M., 1980. The height of handwriting. Acta Psychologica 46, 141–151.
Zesiger, P., P. Mounoud and C.A. Hauert, 1990. Perceptuo-motor and linguistic aspects of handwriting: A developmental study. Communication presented at the Fourth Conference of the European Society for Cognitive Psychology, Como, Italy, September 15–19.
Zesiger, P., P. Mounoud and C.A. Hauert, in preparation. Lexical effect in adults' and children's handwriting production.
Ziviani, J., 1984. Some elaborations on handwriting speed in 7- to 14-year-olds. Perceptual and Motor Skills 58, 535–539.