JOURNAL OF EXPERIMENTAL CHILD PSYCHOLOGY **67,** 164–184 (1997)
ARTICLE NO. CH972400

Dysgraphia in Children: Lasting Psychomotor Deficiency or Transient Developmental Delay?

Bouwien C. M. Smits-Engelsman and Gerard P. Van Galen

Department of Motor Functions and Rehabilitation, Nijmegen Institute for Cognition and Information, University of Nijmegen, Nijmegen, The Netherlands

A longitudinal design was applied to differentiate between normal variations of psychomotor development and lasting handwriting deficiency (dysgraphia). Sixteen primary school children were tested with writing tasks that were recorded on a computer-monitored *XY* tablet. These tasks represented different modules of the handwriting model of Van Galen (1991). Dependent variables were spatial errors, movement time, movement dysfluencies, trajectory length, stroke curvature, and the degree of neuromotor noise in the movement velocity profiles. The latter variable was measured by means of Power Spectral Density Analysis of the movement velocity signal, which revealed that movements of poor writers were substantially more noisy than those of proficient writers, with a noise peak in the region of neuromotor tremor. At the same time, the poor writers were less accurate. It was concluded that control of spatial accuracy rather than allograph retrieval or size control is the discriminating feature in dysgraphic children. Moreover, poor writers do not catch up with their peers within the 1 year time span tested.

Handwriting and drawing are complex motor behaviors in which linguistic, psychomotor, and biomechanical processes closely interact with maturational, developmental, and learning processes (Hulstijn & Van Galen, 1988; Meulenbroek & Van Galen, 1988; Portier, Van Galen & Meulenbroek, 1990). Like other complex motor and linguistic skills such as speech and reading, handwriting requires extended time for a high level of proficiency to develop (Mojet, 1991). This long learning period and its sensitivity to neurological disturbances (Lezak, 1990) make handwriting a useful skill to study develop-

---

We thank the children, parents, and teachers for participation and cooperation. We acknowledge the helpful comments of David Rosenbaum and other reviewers.

Address correspondence and reprint requests to Bouwien C. M. Smits-Engelsman, Department of Motor Functions and Rehabilitation, Nijmegen Institute for Cognition and Information (NICI), University of Nijmegen, P.O. Box 9104, 6500 HE Nijmegen, The Netherlands. E-mail: smits@nici.kun.nl; vangalen@nici.kun.nl.

0022-0965/97 $25.00

mental factors as well as the impact of minor neuromotor dysfunction on proficiency.

Problems in writing and in other school-related motor skills are encountered quite frequently at school and in clinical practice. It is estimated that 5 to 20% of all children show some form of nonoptimal fine motor behavior, including writing disorders (Gubbay, 1975). Writing problems are the most frequently mentioned problems in children with Developmental Coordination Disorder (DSM-IV, 1994) or Clumsiness (Schoemaker, 1992). The common feature of dysgraphic children is that even with the proper amount of instruction and practice, they fail to make sufficient progress in the acquisition of the fine motor task of handwriting. The most frequent complaint about their writing is that they are not capable of producing a good quality script. Dysgraphic handwriting lacks consistency (Keogh & Sugden, 1985) that is not due to carelessness or ignorance. Also, these handwriting problems are typically of a motor nature and are not caused by poor spelling or other psycholinguistic problems (Ellis, 1982; Hamstra-Bletz & Blöte, 1993; Lerner, 1983; Margolin & Wing, 1983; Wann, 1987; Wann & Kardirkamanathan, 1991).

Several authors suggest that the most salient feature of poor handwriting is its variability in size, form, and orientation across repetitions (Wann, 1987; Wann & Kardirkamanathan, 1991). If several replications of the same handwriting pattern are considered, the random variation around the average spatial (or spatio-temporal) pattern may be considered as an estimate of the motor noise inherent in the handwriting task. Wing (1979) suggested that these random variations in handwriting may arise from the noise of the neuromuscular system. Using the same line of reasoning, it might be argued that the control of the amount of noise that is transferred to the spatial domain is a relevant factor in writing performance and handwriting research. Results from Van Galen, Portier, Smits-Engelsman, and Schomaker (1993) suggest that motor development is indeed characterized by increased efficiency in inhibiting noise in the neuromotor and muscular system.

Traditional handwriting research has focused on analyzing the *product* of handwriting activity. Descriptive research in the field of handwriting has helped to gain insight into several aspects of poor handwriting performance, including letter formation quality, size and slant control, and pen-holding postures (Hamstra-Bletz, De Bie, & Den Brinker, 1987). Also, developmental changes (Blöte & Hamstra-Bletz, 1991; Mojet, 1991) related to writing speed and the form features of script have been well documented. For instance, descriptive, product-oriented approaches have made clear which criteria must be met for script to be legible (De Ajuriaguerra & Auzias, 1975), what kind of malformations in letter forms are found, which letters are most important for legibility (Freeman, 1954), and how distance between letters and words affects legibility (Alston, 1983). Typical developmental discoveries are that model letter forms change into personal letter forms during adolescence (Hamstra-Bletz & Blöte, 1993; Weinert, Simons, & Essing, 1966; Wing, Watts, &

Sharma, 1991). Further, there are significant differences in the spatial accuracy of writing at different ages (Askov, Otto, & Askov, 1970; Søvik, 1975).

The Locus of Handwriting Deficit

To understand normal handwriting, but also to help restore handwriting deficiencies, it is essential to relate handwriting performance to its underlying processing modules (Smits-Engelsman, Schoemaker, Van Galen, & Michels, 1996; Van Galen, 1991). Therefore an alternative to merely describing the quality of the handwriting product is to focus on the processes underlying the production of the handwriting movements. In the present study it is argued that to disentangle developmental processes and psychomotor deficiencies, an understanding of the *motor control processes* that lead to the product is vital.

In our research, a task-loading research design is used to localize deficiencies and/or developmental delays in relevant motor processing stages. In this ‘‘task-loading’’ research strategy, tasks were designed to measure a subject’s sensitivity to specific processing demands. Specific task demands such as slow versus rapid allograph alternation and wide versus narrow lineation boundaries were chosen to represent particular stages of the handwriting model of Van Galen (1991).

The model has been used to investigate to what extent dysgraphia may be explained as the result of a malfunction of one of the postulated component processes of the psychomotor system. Van Galen (1991) summarized neuropsychological and experimental evidence to support the following three processing modules in the performance of motor tasks: (1) Motor Programming, or the retrieval of an allograph action pattern from long-term motor memory. (For example, when asked to draw a capital E, subjects activate a general sequence of drawing strokes, irrespective of their size and irrespective of the musculature which will be used in their realization.); (2) Parameterization, or the processing step by which the overall force level, tempo, and size of the task performance is regulated; and (3) Muscular Initiation, or the process of neurological recruitment and muscular initiation of the motor units that are appropriate for a task in a given biomechanical context. This last module is thought to be responsible for the remarkable constancy of motor acts in an ever-changing biophysical environment.

Previous cross-sectional studies that were designed along these lines (Smits-Engelsman, Van Galen & Portier, 1994a, 1994b; Van Galen, Portier, Smits-Engelsman & Schomaker, 1993) suggest that poor handwriting is related to the peripheral, muscular initiation process and that the most salient feature is poor neuromotor noise management. The aim of the present study is to validate this hypothesis using a longitudinal approach. Moreover, a specific hypothesis to be tested is that poor handwriting and the corresponding noisiness of the handwriting velocity signal are stable individual traits and are not signs of a transient developmental delay.

Neuromotor Noise and Psychomotor Development

Normal motor development is characterized by increased consistency in motor performance (Williams, Woollacott, & Ivry, 1992). The nervous system learns to control the timing and activation of the movement, and the biomechanical effector transforms the noisy neuronal signal into a smooth, spatial signal. The most important determinant of skill level is probably the amount of practice, but there are other factors that affect the level of performance. Dexterity is one factor that is not a property of the motor act itself but rather of its interaction with the changing environment (Latash & Latash, 1991). To achieve spatially accurate writing, the neurological recruitment and muscular initiation of the motor units must, therefore, be appropriate for a task within a momentary biomechanical context. However, given a proficient and mature neuromotor system and unlimited practice, there is still a limit to movement precision and consistency. Movement proficiency may be limited by the inherent noisiness of the muscular system and by suboptimal strategies the human subject has adopted to filter noise by features such as stiffness and viscosity (Van Galen & De Jong, 1995). In the present article, we argue that in a natural task situation like handwriting it is the balance between producing signal (specific letter forms) and noise that is a critical task demand, the failure of which is a typical feature of dysgraphia in children.

A New Measure to Estimate Neuromotor Noise

A new measure, developed by Van Galen and Schomaker (1992), was used to estimate the noisiness of children's movements. A basic assumption of the measure is that one of the causes of spatial inaccuracy lies in the inherent variability of the motor output system. This so-called neuromotor noise is considered to be a dynamic influence on the spatial endpoint variability of movement. The method makes use of Power Spectral Density Analysis to estimate the relative contribution of noise to the total energy in a recorded movement signal. Power Spectral Density Analysis is a mathematical method in which Fast Fourier Analysis is used to decompose the energy in a time function of a recorded movement signal (e.g., the velocity profile of a writing stroke from the start of the movement until the end) into its frequency components. For the application of the method, it is assumed that observed variation of movement velocity is a periodic signal which basically is the summed outcome of various periodic sources of variation. Each source of variation has its own typical frequency. In adult handwriting, writing strokes are delivered with a pace of 10 strokes per second (Teulings & Maarse, 1984). The overall frequency of the up and down movement cycle will be 5 Hz. However, superimposed upon the overall pacing, feedback-based corrections, tremors, recruitment noise, and mechanical oscillations add energy to the periodical signal. In the present experiment, Power Spectral Density Analysis is used to measure the remaining energy in the velocity profile of movements after the energy related to the overall frequency of the movements has been subtracted. What is then actually measured after this substraction is a *deviation spectrum* which reflects the periodical fluctuations of the signal caused by corrections, tremors, and mechanical oscillations. Details of the method have been described in Van Galen, Van Doorn, and Schomaker (1990) and Van Galen, Portier, Smits-Engelsman, and Schomaker (1993). In the latter study, Power Spectral Density Analysis was applied to the velocity profile of experimental handwriting tasks performed by poor and proficient writers to estimate the degree of neuromotor noise in their movement profiles. Results showed that energy in the 4–7 Hz band of the velocity profile is related to poor handwriting. The origin of this noise component is most likely neuromotor tremor.

Handwriting Development and Dysgraphia

Earlier cross-sectional research on the development of handwriting revealed certain significant developmental features (Smits-Engelsman et al., 1994a,b). One of the findings was that in young children (8 years of age) the retrieval of the motor program was a critical task demand: the production of strings of varying letters was substantially slower and more dysfluent than simple repetitions of arcades and garlands. This difference disappeared in older children. As to size control, younger children had more difficulty producing larger letter sizes, probably because of their failure to plan and execute larger line trajectories. However, it was found that with increasing age, poor and proficient writers exhibited the same increase in performance with respect to motor program retrieval and size control. At the same time, it was found that poor writers of all age groups made more spatial errors, especially when high accuracy demands were prevalent.

This earlier work implies that poor handwriting is primarily a problem of poor spatial control and that poor handwriting and poor noise management are interrelated and stable traits. From the theoretical perspective developed by Van Galen and De Jong (1995), failing to inhibit the natural degree of neuromotor noise is the most likely cause of poor handwriting. Furthermore, in the cross-sectional studies the deficiencies did not appear to be an age-related developmental delay. At the individual level, however, no empirical evidence of the persistence of the trait is yet available. Therefore, to add further evidence to the theory and to test it in a longitudinal design, the present follow-up study was performed on a subset of the subjects who were featured in the previous studies (Smits-Engelsman et al., 1994a,b; Van Galen et al., 1993). Basic features of the children's motor performance (e.g., the sensitivity to spatial constraints) were measured in a longitudinal design and by means of the task loading method, described above. In addition to such normal kinematic measures as movement time, dysfluencies, and spatial errors, the degree of neuromotor noise was measured by means of Power Spectral Density Analysis.

The specific research questions that were addressed were as follows. First, does the sensitivity to spatial demands change during a 1 year period in children between 7 and 12 years of age? Second, are these changes different for proficient and poor writers? It was predicted that both poor and good writers would show an improvement of writing skill as expressed by movement time, movement dysfluency, and writing trace curvature; although, with respect to accuracy control, it was expected that poor writers would be stable over the 1 year period.

METHODS

Participants

Forty-eight pupils (ranging in age from 7.6–11.0 years, mean 9.1) from ten different elementary schools spread over the Netherlands were selected on the basis of their handwriting proficiency from a larger sample of 634 children (ages ranging between 7.6 and 12.6 years) in Grades 2, 3, and 4. The children were rated for their handwriting achievements during the previous school year by their own teachers. In the conventional Dutch grading system, ratings can range from 1 to 10, in which 1 stands for extremely poor, 6 for just sufficient, and 10 for excellent performance. Subjects with a rating score of 5 or lower for their average handwriting performance in school were assigned to the *poor group* (n = 183; 21.6%), whereas subjects who received a rating score of 7 or higher were assigned to the *proficient group* (20%). From the poor group (n = 183), a stratified sample of 24 children were selected to be included in the research. Within this group 8 children each were in the second, third, and fourth grades. These children were matched for sex, age, handedness, and school grade with 24 children from the group of proficient writers. The average ages for the children in Grades 2, 3, and 4 were 8.0, 9.0, and 10.0, respectively. Inclusion and exclusion criteria for the study were that the children (ages 7–12) were capable of cursive writing, had no known neurological problems, and attended regular school classes.

One year later, half the schools that had participated in the cross-sectional study (Smits-Engelsman et al., 1994a) were asked, on a random basis, to cooperate again, which they all did. Therefore, from the original sample of 48 children, 24 were invited to take part in the experiment 1 year later. Because 4 children were no longer at the same school, they (and their matched controls) did not participate in the second experiment. Thus, 8 matched pairs (n = 16; 6 girls and 10 boys) remained. Due to technical problems, some of the data for one child were unusable.

As a measure of control, we checked to see if the sample of our longitudinal group (n = 16) was representative of the cross-sectional research sample (n = 48). To this end we performed a discriminant analysis on all the sets of data (selection criteria, experimental data, and psychomotor covariables) available for the children. No significant differences in these analyses were found between the two samples. It may thus be concluded that the second

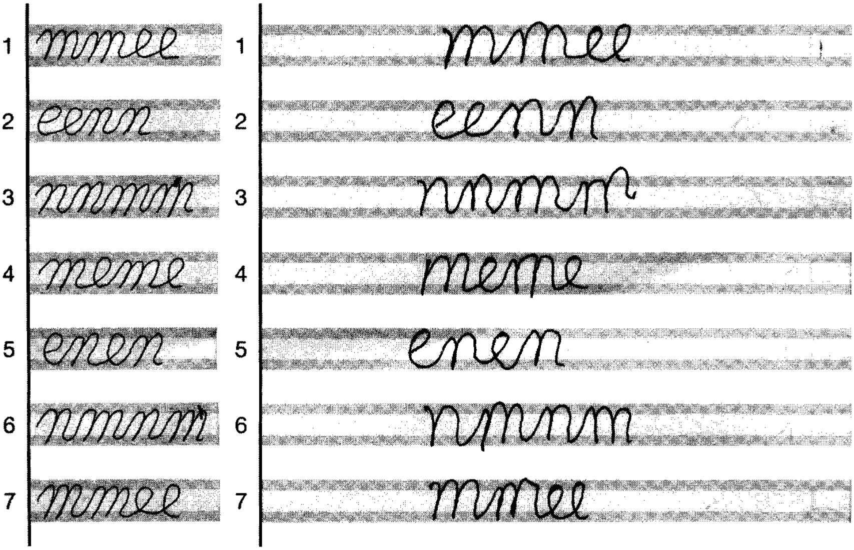

FIG. 1. Two samples of writing as produced in the experiment by a proficient (left) and poor writer (right). The figure demonstrates the target and compliance zones. Here, the large letter size and high accuracy condition is shown.

sample of writers in the longitudinal investigation represents a true sample of the children in the cross-sectional part of the study.

Tasks and Materials

An example of a sheet with writing tasks as they were performed by the subjects is given in Fig. 1. The writing tasks used in the experiment consisted of short strings of connected script of varying difficulty. To test a child's letter formation ability (allograph retrieval), the production of simple garlands and arcades was compared with the production of letter strings of varying complexity. This first task variable will be referred to as ''allograph retrieval load.'' To establish a baseline performance (Level 1), we used simple garlands and arcades which are similar to stroking patterns used in ''eee's'' and ''mmm's,'' respectively. This task condition was used because it was assumed to put the smallest load on motor program retrieval. In addition to this control condition, a task condition was used which was assumed to place a heavier load on the motor program retrieval stage. For the Level 2 task, changing letter patterns like in ''eenn'' or ''meme'' were used. The letters ''e'' and garlands have an overall anticlockwise movement continuation, whereas letters ''n'' and ''m'' like arcades have a clockwise continuation.

Size control was measured by giving writing tasks of varying sizes (writing size). This second task variable was introduced to manipulate the process of parameterization. We varied the size demand at two levels. All letter sequences had to be written either small (3-mm average height of the letters) or large (6-mm average height). The two levels of size control were indicated through the lineation on the writing forms, i.e., through the vertical distances of the shaded target zones that indicated upper and lower boundaries of the letters in each of the two size conditions. The lineation as used in the large size condition is illustrated in Fig. 1.

The third variable was associated with writing accuracy, which was assumed to load on the muscular initiation stage. For the production of accurate script, a delicate tuning of hand and finger musculature and the capability to adjust to the varying biophysical context are critical prerequisites. To vary the degree of accuracy, upper and lower target zones along the lineation were defined as the range within the vertical extremes of the letters that were allowed (see Fig. 1). Consequently, the subject was not supposed to write exactly between lines but to stay within an upper and lower zone of compliance. The width of this target zone was varied at two levels within each size condition and was either $\frac{1}{3}$ or $\frac{1}{6}$ of the normal letter size.

Procedure and Apparatus

The experiment was conducted at the pupils' schools. Each subject was tested individually. Subjects who were tested twice received no treatment or special training for their writing problems between the two measurements. Teachers were not told about a reassessment until 2 weeks before retest. Each pupil was given several practice trials in order to become acquainted with the experimental setting. The writing experiment took about 30 min for each pupil. Each trial began with the presentation of a stimulus on the computer monitor, which was placed approximately 50 cm in front of the pupil. Each stimulus was presented for 2 s, followed by an auditory starting signal which marked the beginning of the registration time. During this registration time, the pupil was required to copy the stimulus in the following 10 s. During the registration time the letter sequence remained on the screen. The end of the registration time was also indicated by an auditory signal. The pupil was instructed to write in such a way as to prevent over- or undershoots of the target zones. There was no instruction about speed.

The apparatus included an MS-DOS PC (80386 processor) and software for sampling the position of the pen during a writing task, a digitizer tablet (CALCOMP 2300), an AD/DA interface, and a special pen (Maarse, Janssen, & Dexel, 1988) with a built-in pressure sensing device. The pen was connected to the writing tablet by a light plastic wire. During the experiment, the children were seated on a chair that was adaptable to their body height. The X and Y coordinates of the pen, as well as the axial pen force exerted on the pen point (Z), were sampled with a frequency of 100 Hz and were spatially accurate to within 0.2 mm.

Design

Differences in performance, after a 1 year period, between poor and proficient writers (matched for age and grade) were analyzed by comparing the effects of task demands (within subjects) in a repeated measures (1 year later) design, on the following dependent variables: overshoots, undershoots, movement time, writing dysfluencies, stroke curvature, and the relative amount of noise in the velocity signals of the writing tasks (Power Spectral Density Analysis). Each pupil performed each of the writing tasks according to a randomized block design.

Data Analysis

Writing trajectories were displayed for inspection and analyzed by means of an interactive computer program. Segment boundaries were determined by searching for those minima in the absolute velocity pattern of the recorded writing movement that coincided with consecutive up and down strokes. For the analysis of the dependent variables, the first segment was excluded because of the large variability of the first upstroke. The remaining segments were used for further analysis. For all records the following variables were calculated and averaged over trials for each condition and subject: movement time, trajectory length, writing dysfluencies (defined as above chance level inversions of the sign of the velocity signal), and stroke curvature (integrated angular displacement over the full trajectory of a letter stroke). Furthermore, two spatial error measures were defined, namely the number of times the pupil made an overshoot (the outer limit of one of the target zones was crossed) or an undershoot (the inner limit of one of the target zones was not reached).

The digitizer tablet recorded writing movements in two dimensions; horizontal (X dimension) and vertical (Y dimension). The data from the digitizer tablet were stored in the hard disk of the PC which controlled the experiment and was transferred to a VAX computer system for further data analysis. For each child and for each replication of a writing task, separate data records were collected containing the position of the pen tip over time for the X and the Y dimensions with a temporal resolution of 100 Hz and a spatial resolution of 0.2 mm. Then, by a semiautomatic segmentation procedure, each recorded task word was segmented into consecutive up and down strokes. The computer algorithm that was used for this stage of the procedure searched for points of minimal absolute velocity, and the experimenter decided, based on visual inspection of the vertical position of the minima whether these points were the beginning or end of an up or down stroke. After segmentation of the data records, for each individual stroke the X and the Y dimensions were redefined by rotation of the coordinates such that the rotated X dimension (now called X') represented the movement direction perpendicular to the overall slant of that stroke, and the rotated Y dimension (now called Y') was identical to the stroke's overall slant. Slant, here, is defined as the angle between the base line of writing and the line going through the beginning and end of a stroke. So, after segmentation and rotation, the X' dimension was representative of corrective movements and the degree of curvature of a stroke, whereas the Y' dimension was indicative of movement along the overall direction of movement. The energy related to the latter dimension usually was the largest.

For each recorded stroke, respectively, the velocity profiles of movement in the X' and Y' dimensions were used to derive Power Spectral Density Functions, representing the noise contained in these profiles. First, average velocity signals (for the X' and Y' dimensions) were calculated for each subject and task condition separately. Next, from each recorded velocity profile the corresponding average signal was subtracted. This step of the procedure resulted in velocity deviation signals for each recorded writing stroke. Then, again for each subject and task condition, an algorithm using fast Fourier transform analysis was applied to derive Power Spectral Density Functions of the resultant velocity profiles (ranging from 1 to 49 Hz and for the X' and Y' dimensions separately). The goal of this procedure was to remove all energy from the frequency spectrum of a stroke that was related to the overall speed and spatial form of that stroke. It should be remembered that our theory was centered around the concept of neuromotor noise and the present procedure was used to arrive at a best estimate of the noisiness of writing movements in different task conditions and subjects. The calculated spectrum is a *deviation spectrum* which is representative of the noise components of each individual movement. From each recorded writing stroke only the middle 70% of the data points were used for the calculation of these deviation or noise spectra. This procedure reduced the likelihood that the resulting Power Spectral Density Function would be contaminated by mechanical perturbations during the start and end phase of a movement.

For each subject and task condition, an average deviation spectrum (for X' and Y' dimensions separately) was then entered into a procedure that integrated bandpower (between 1 and 49 Hz) in 16 subsequent bands of 3 Hz. These 16 bands−spectra were expressed either as absolute spectra or as relative spectra. Absolute power spectra were used as an estimate of the overall degree of noise in the writing movements of poor and good writers in different task conditions. However, these spectra were easily contaminated with physical effects such as movement velocity and stroke length. Therefore, relative power spectra were used by dividing the power scores in each band by the summed power of the whole spectrum (Van Galen, Van Doorn, & Schomaker, 1990; Van Galen & Schomaker, 1992; Van Galen et al., 1993).

For the analyses a mixed-model univariate analysis of variance was chosen because it is more powerful for small sample sizes. The univariate analyses of variance were carried out on the mean values of the dependent measures for each child, according to a design with independent variables represented by the above-mentioned between-subjects variable (poor versus proficient) and the four within-subjects variables (two levels of time of test, two levels

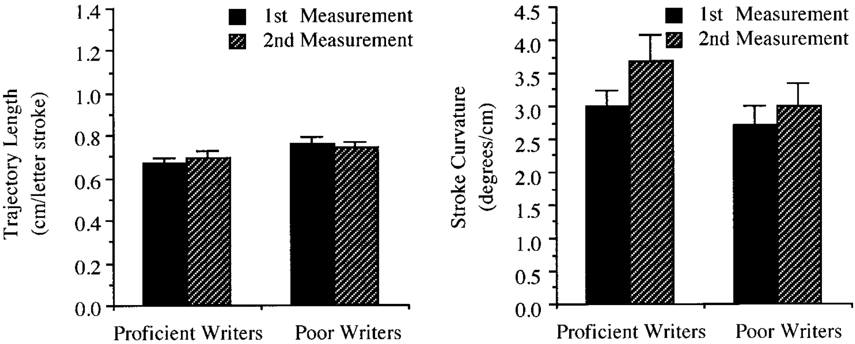

FIG. 2. Average letter stroke length (left) and average letter stroke curvature (right) for writing tasks written by proficient and poor writers, at the first and second measurement, respectively.

of allograph retrieval, two levels of writing size, and two levels of accuracy). An alpha level of .05 was used for the statistical tests.

RESULTS

Kinematic Analysis

Proficiency

Significant main effects of proficiency were found for trajectory length ($F(1,275) = 35.18$, $p < .001$), stroke curvature ($F(1,275) = 4.84$, $p < .05$), overshoots ($F(1,275) = 3.33$, $p < .05$), and undershoots ($F(1,275) = 6.79$, $p < .05$) but not for movement time ($F(1,275) = 2.02$, $p = .16$) or writing dysfluencies ($F(1,275) = 0.26$, $p = .61$) (Figs. 2–4). Poor writers made four times as many overshoots and five times as many undershoots as good writers. Good writers used more curved letter strokes (Fig. 2, right), wrote letters about 10% smaller (Fig. 2, left), and made fewer spatial errors (Fig. 3); however, they did this with the same number of dysfluencies (Fig. 4, left) and within about the same movement time (Fig. 4, right) as poor writers.

Time of Test

The longitudinal comparison revealed significant effects of time of test on movement time ($F(1,275) = 70.01$, $p < .001$), dysfluencies ($F(1,275) = 318.87$, $p < .001$), stroke curvature ($F(1,275) = 4.48$, $p < .05$), and overshoots ($F(1,275) = 4.73$, $p < .05$). Movement time decreased about 20% over the year (510 ms versus 400 ms per stroke), while the length of the movement trajectories did not change ($F(1,275) = 0.07$, $p = .79$). The number of dysfluencies in each movement trajectory decreased substantially (50%) and stroke curvature increased. The number of overshoots per letter sequence decreased by 10%. Together, these data show that after a 1 year period writing

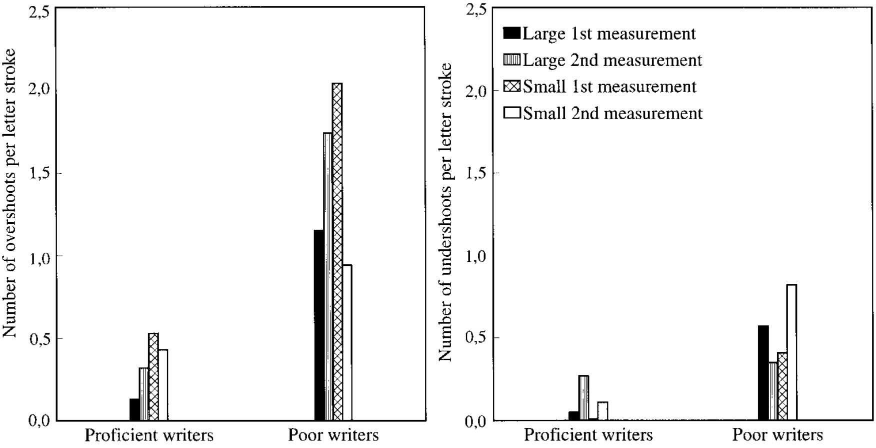

FIG. 3. Average number of overshoots (left) and undershoots (right) for large and small writing tasks written by proficient and poor writers, at the first and second measurement, respectively.

movements were faster, letter forms were more rounded, and on average vertical strokes ended less often beyond the target zones.

Interactions between Proficiency and Time of Test

As mentioned above, movement time decreased between the first and second measurement. However, an interaction between proficiency and time of

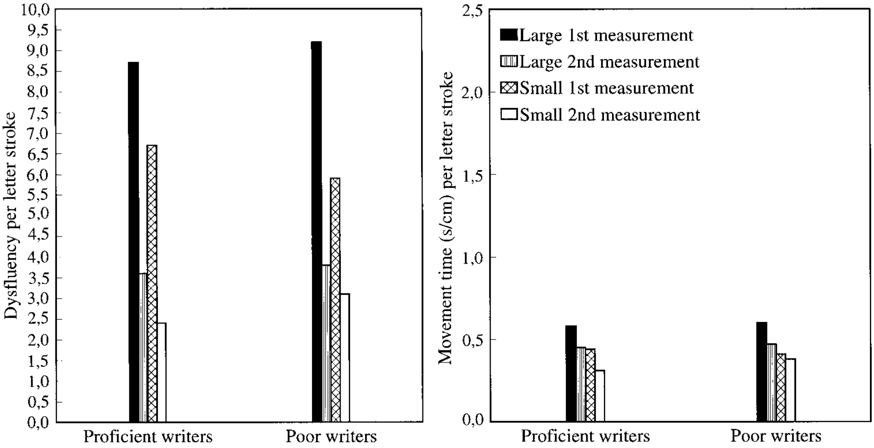

FIG. 4. Writing dysfluency (left) and movement time (right) per letter stroke for large and small writing tasks written by proficient and poor writers, at the first and second measurement, respectively.

test was found ($F(1,275) = 4.17$, $p < .05$). The movement time means indicated that good writers improved their writing speed more than poor writers (Fig. 4, right). As to effects in the spatial domain, it appeared that changes over time for the length of the movement trajectories were different for good and poor writers ($F(1,275) = 4.46$, $p < .05$). Trajectory length *increased* for good writers and *decreased* for poor writers (Fig. 2, left). The opposite direction in the development of writing size between good and poor writers may explain why the main effect of time of test was not significant. As a result of this developmental trend, differences in trajectory length per segment between good and poor writers diminished from 0.09 to 0.05 cm 1 year later.

Interactions between Proficiency and Task Demands

The analyses revealed no significant interactions ($p < .05$) between the levels of proficiency and allograph retrieval, writing size, and accuracy with respect to the kinematic variables. However, significant second-order interactions were found between proficiency, task demands, and time of test. The results showed differences in time of test between the poor and proficient writers for the effects of size variation. One year later, poor writers made more overshoots in the larger letter condition ($F(1,275) = 4.13$, $p < .05$) and more undershoots ($F(1,275) = 5.08$, $p < .05$) in the small letter condition (Fig. 3). In contrast, good writers showed a more consistent writing performance. Also, the number of dysfluencies and movement time revealed significant differences in time of test between good and poor writers in the different size conditions. In statistical terms this conclusion is evidenced by the two significant second-order interactions between proficiency, time of test, and size for the fluency and the movement time measurements, $F(1,275) = 3.87$, $p = .05$ and ($F(1,275) = 4.17$, $p < .05$), for dysfluency and movement time, respectively. The means of the fluency and the movement time data are shown in Fig. 4. It can be seen that, 1 year later, the large difference between the number of dysfluencies in the large and small size conditions no longer existed and that this effect was more pronounced in the poor writers than in the good writers. The decrease in movement time was greater for good writers than for poor writers, especially in the small size condition, where poor writers showed little reduction in movement time.

The analyses revealed no further significant second-order interactions between proficiency, time of test and allograph retrieval, and accuracy with respect to the kinematic variables.

Noise Spectra

Absolute Power Spectra

Proficiency. The ANOVAs on the absolute power scores revealed strong effects of proficiency. The Power Spectral Density Functions of the poor

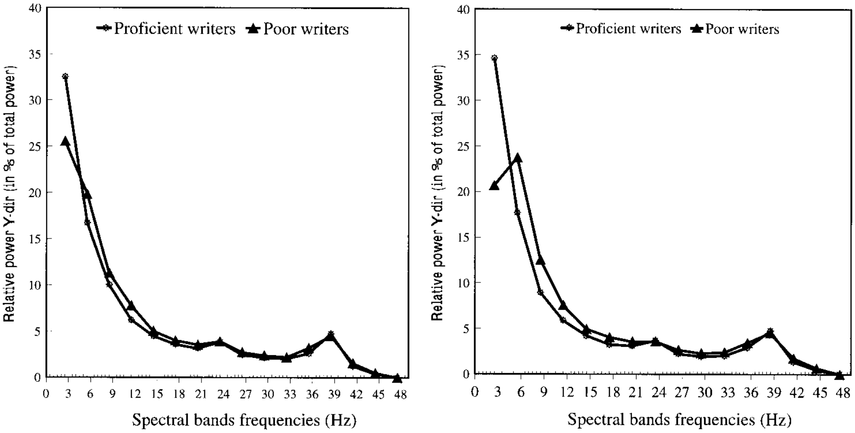

FIG. 5. Power spectral density functions (relative power) for the velocity profiles of writing strokes of poor and proficient writers at the first measurement (left) and the second measurement (right), respectively.

writers showed that twice as much noise was present in their movement velocity profiles than in those of the proficient writers (2.5 Hz: $F(1,240) = 29.70$, $p < .0001$; 5.5 Hz: $F(1,240) = 35.69$, $p < .0001$; 8.5 Hz: $F(1,240) = 18.22$, $p < .0001$) and this applied to the first as well as the second measurement (Fig. 5). A primary conclusion might be that writing movements of poor writers are characterized by higher absolute noise levels. This was especially true for the 5.5- and the 8-Hz bands which probably are representative of neuromotor tremor. It should be remembered that there are several alternative explanations for the higher energy in the absolute power spectrum, such as differences in speed and distance. Therefore, the evidence for a higher proportion of tremors and other sources of noise has to be corroborated by analysis of the relative power profiles (see below).

Time of test. The Power Spectral Density Functions of the absolute power scores for the second measurement exhibited significantly higher power scores than for the first measurement (2.5 Hz: $F(1,240) = 33.69$, $p < .0001$; 5.5 Hz: $F(1,240) = 33.78$, $p < .0001$; 8.5 Hz: $F(1,240) = 24.73$, $p < .0001$; 11.5 Hz: $F(1,240) = 17.09$, $p < .05$). This phenomenon must be interpreted to be due to the physical effect of the significant increase in movement velocity over time. The effects of proficiency and time of test on the absolute Power Spectral Density Functions of the velocity profiles in the Y' direction are depicted in the left and right panels of Fig. 6. As explained above, the velocity profiles for the Y' direction of writing strokes correspond to the overall orientation of the stroke.

Effects in the X' direction were comparable to those in the Y' direction, though less pronounced. The latter, of course, is to be expected because the

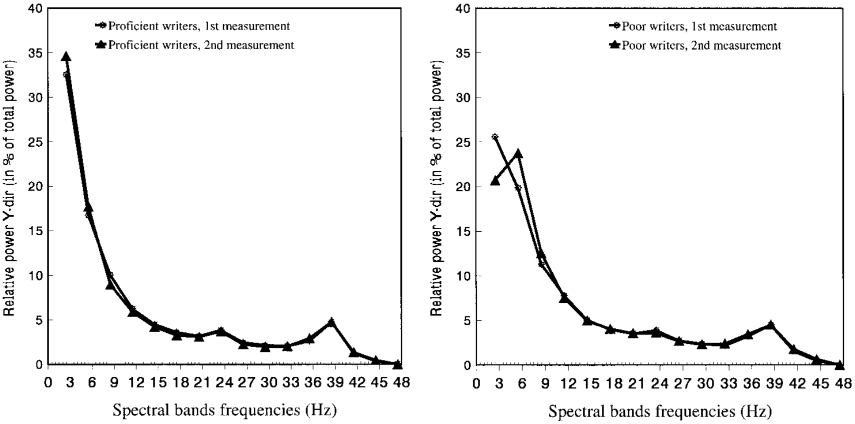

FIG. 6. Change of the form of the power spectral density functions (relative power) for the velocity profiles of writing strokes over a 1 year period for proficient writers (left) and poor writers (right), respectively.

larger proportion of the energy contained in the absolute Power Spectral Density Functions is related to propulsion of the pen along the overall direction of a stroke.

Interactions between proficiency and time of test. A significant interaction between proficiency and time of test for the 5.5-Hz frequency band was found ($F(1,240) = 7.61$, $p < .01$). In proficient writers, time of test did not affect the form of the spectra over a 1 year period, whereas for poor writers, the Power Spectral Density Analysis technique revealed a significant increase in the 5.5-Hz peak. From this finding, it may be concluded that the greater proportion of energy in the range of the spectrum that is most likely to be an expression of neuromotor tremor is even increased in the group of poor writers after a 1 year period.

Relative Power Spectra

The results of the ANOVAs on the relative power scores have been depicted in Fig. 6 (Y' direction only). Main effects were found for proficiency (2.5 Hz: $F(1,240) = 11.41$, $p < .0001$; 5.5 Hz: $F(1,240) = 9.82$, $p < .01$; 8.5 Hz: $F(1,240) = 17.16$, $p < .0001$) and time of test for the X' and Y' directions (5.5 Hz: $F(1,240) = 20.52$, $p < .0001$). In the lowest band (midpoint 2.5 Hz), good writers had relatively more power than the poor group. The effect may be an expression of the greater role of corrective movements in good writers. Voluntary movements are known to require intermittent feedback for accuracy, and tracking visual targets can result in rapid positional corrections at up to 3 to 4 Hz (Miall, Weir, Wolpert, & Stein, 1993). However, in the higher 5.5- and 8.5-Hz bands, this pattern was reversed: poor writers were characterized by higher power in these bands. The origin of the peaking of power in this region of the spectrum is attributed to neuromotor tremor and recruitment noise (Van Galen et al., 1990). Figure 6 permits a comparison of the form of the relative spectra over a 1 year period for proficient and poor writers, respectively. Whereas proficient writers (left) develop consistently to a noise profile in which the lower frequencies take over from the higher, in poor writers (right) a reversed evolution takes place. In the latter group the lowest frequency decreases and the cost of an increase in ranges is related to tremor and to recruitment noise.

DISCUSSION

The results from this longitudinal study are consistent with the results of earlier cross-sectional studies (Smits et al., 1994a,b; Van Galen et al., 1993). The findings support the view that poor psychomotor skill persists in individual children over time, at least for the 1 year time span considered. At the same time, however, the 1 year follow-up shows that the good and the poor writing children increased writing velocity and used more ballistic movement trajectories. Analogous data were obtained in Mojet's study (1991), in which speed increased linearly from 50 to 110 characters per minute from 8 through 12 years of age. In Mojet's study also, poor handwriting persisted over the time span studied, regardless of a normally developing production rate. In the procedure used by Mojet no task demands were varied to locate the poor writing deficit. Hamstra-Bletz and Blöte (1993), who applied qualitative handwriting appraisal in a longitudinal design, produced comparative findings. It may be concluded that without extra help dysgraphic children appear unable to produce a good quality script and they make little progress in the acquisition of handwriting in a 1 year period. Caution in drawing conclusions about continued handwriting difficulty is needed, however, because neither investigation included intervention. Poor handwriting may be a persistent trait when untreated, but it may be sensitive to training. If poor handwriting is the effect of a noisy neuromuscular system, it may be that better movement strategies help to improve the handwriting product. Support for this view is found in Smits-Engelsman et al. (1996) that children's poor handwriting improved after a specific physiotherapy program.

The present study focused specifically on identifying the type of failure of the psychomotor system that could inhibit the poor writer's ability to keep the natural irregularity of the writing trace within acceptable limits of readability and good appearance. We conclude that poor writing is not primarily related to a failure of the motor programming process or of overall letter size production. Instead, poor writers fail to obey spatial constraints, and their handwriting lacks consistency. Dysgraphic children showed more variability in size, resulting in spatial inaccuracy of the writing product. Their letter sizes were more inconsistent: half their letters were too large in the large letter condition and nearly one out of four letters was too small in the small letter condition. Furthermore, poor writers showed less curvature in their strokes.

Not only does this study show that poor writers do not catch up with their age-mates, it also reveals an increase in the sensitivity to accuracy demands over a 1 year period. From the kinematic and noise spectra it can be concluded that the failure to control spatial accuracy is the most salient discriminating feature between poor and good writers. It can also be concluded that noise spectra are sensitive measures of the differences in motor proficiency. The alternative hypothesis that dysgraphia is a transient developmental delay and that children may grow out of it was not supported by the present research. Caution, however, is necessary because of the limited time span studied and because of the small numbers of participants in the experiment.

From a process-oriented point of view, our data suggest that poor writers are characterized by poor muscular initiation. This implies that poor writers suffer either from an inherently noisy neuromotor system per se or from a dysfunction in controlling the inherently noisy neuromotor system. In the latter case, the spatial inaccuracy may be the result of their less than optimal strategies to manage neuromotor noise. Stated differently, inadequate biomechanical adaptation to minimize spatial variability may be the cause of poor handwriting. Notwithstanding a normally developing production rate, this less effective management of natural neuromotor noise remains even more evident in poor writers over a 1 year period.

Current research suggests that the neuromotor system may use various means to control this dynamic endpoint variability of movements. First, the writer can reduce the noise that enters the desired movement by producing small force pulses (Schmidt, Sherwood, Zelaznik, & Leikind, 1985; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). This can be done by choosing a slow movement pace. In handwriting, relatively small forces are used, which predicts recruitment of relatively small motor units according to the size principle (Henneman, 1979). The size principle states that the size of the newly recruited units increases with the tension level to be produced. This means the smallest unit is recruited first and the largest last. In this manner, low tension movements can be achieved in finely graded steps. Muscles of the fingers have a small number of fibers per motor unit. Just before one motor unit reaches its maximum firing rate, a new unit is recruited. Units usually drop out in a reversed order to that in which they were recruited. Moreover, small (finger) muscles can also adjust force by subtle changes in firing rate (Van Boxtel & Schomaker, 1983). Poor writers may not be capable of distal writing movements with these small motor units, and therefore, use a less-finely graded, more proximal effector system.

A second strategy to reduce the effect of motor noise is to change the degree of antagonistic cocontraction (Van Galen & Schomaker, 1992). Increased cocontraction of antagonistic muscles may reduce the effects of neuromotor noise on the movement outcome by enhancing the stiffness or viscosity characteristics of the effector joint. Stiffness and viscosity of a limb are dynamical parameters of the movement system which are the continuously changing effects of muscle forces. Of muscle and joint tissue characteristics, Van Galen and De Jong (1995) demonstrated that stiffness and viscosity have a filtering effect on the endpoint accuracy of movement. However, there is a limit to increasing stiffness, because the cocontractions of antagonistic muscles produce an increase in neuromotor noise by their own recruitment.

A third strategy to reduce spatial inaccuracy is to push harder against the surface upon which movements are applied. An example of this strategy is found in the increased pen pressure levels found when subjects perform graphic tasks under conditions of stress (Van Galen & Van Gemmert, 1996; Van Gemmert & Van Galen, in press). By pressing harder on the pencil the friction forces between the tip of the pencil and the paper surface will increase. In biomechanical terms, this leads to increased filtering of the movement signal. It is a strategy commonly observed in children who learn to write. Although the strategy may be effective in reducing tremors and unwanted movement components, it has a cost as well as a result of the fact that increased tonic muscle contraction leads to fatigue and, eventually, tissue damage.

If we consider the options that dysgraphic children have to increase the efficiency of noise inhibition, it is obvious that they do not choose to slow the movement pace. Although not tested in this study, it is also unlikely they use increased pressure against the writing surface to reduce spatial inaccuracy. In none of our earlier studies did we observe overall differences in pen pressure between proficiency (Smits-Engelsman et al., 1991). A likely option is that, in writing tasks, poor writers may incapable of precisely controlling distal movements, but instead use the wrist or even the elbow as pivots of action. By doing so, larger motor units are recruited so that less finely graded movements occur. At the behavioral level, this neuromotor control dysfunction may explain the inconsistent, crude, and dysmetric appearance of the dysgraphic performance in poor writers (Wann & Kardirkamanathan, 1991). Further research is needed to disentangle these alternatives.

A final point should be made about the generality of the findings for tasks other than writing and drawing. The suggestion that poor writers fail to tune their distal musculature precisely does not imply that they necessarily perform poorly in other distal and/or proximal motor tasks. Although we have found evidence for the proposition of a more general dystactical performance in poor writers (Smits-Engelsman, Van Galen, & Schoemaker, in press), characterized by a predominance of too rapid movements, too many errors, and too little adaptation to increased accuracy demands, there are many tasks in which they are just as good or better than their peers.

REFERENCES

Alston, J. (1983). A legibility index: can handwriting be measured? *Educational Review,* **35,** 239–242.

Askov, E., Otto, W., & Askov, W. (1970). A decade of research in handwriting: Progress and prospect. *Journal of Educational Research,* **64,** 100–111.

American Psychiatric Association. (1994). *Diagnostic and statistical manual of mental disorders* (4th ed.). Washington, DC: Psychiatric Association.

Blöte, A. W., & Hamstra-Bletz, L. (1991). A longitudinal study on the structure of handwriting. *Perceptual and Motor Skills,* **72,** 983–994.

De Ajuriaguerra, J., & Auzias, M. (1975). Preconditions for the development of writing in the child. In E. Lenneberg & E. Lenneberg (Eds.), *Foundations of language development* (Vol. 2). New York: Academic Press.

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.

Freeman, F. N. (1954). *Teaching handwriting—What research says to the teacher* (4th ed.). Washington: Association of Classroom Teachers of the National Education Association.

Gubbay, S. S. (1975). *The clumsy child.* Philadelphia: Saunders.

Hamstra-Bletz, L., & Blöte, A. W. (1993). A longitudinal study on dysgraphic handwriting in primary school. *Journal of Learning Disabilities,* **23,** 689–699.

Hamstra-Bletz, E., De Bie, J., & Den Brinker, B. P. L. M. (1987). *Beknopte beoordelingsmethode voor kinderhandschriften* [A brief evaluation method for children's handwriting]. Lisse: Swets & Zeitlinger.

Henneman, E. (1979). Functional organization of motor neuron pools: The size-principle. In H. Asanuma & V. J. Wilson (Eds.), *Integration in the nervous system* (pp 13–25). Tokyo: Igaku-Shoin.

Hulstijn, W., & Van Galen, G. P. (1988). Levels of motor programming in writing familiar and unfamiliar symbols. In A. M. Colley & J. R. Beech (Eds.), *Cognition and action in skilled behaviour* (pp. 65–85). Amsterdam: Elsevier.

Keogh, J., & Sugden, D. S. (1985). *Movement skill development.* London: Macmillan.

Latash, L. P., & Latash, M. L. (1991). A new book by N. A. Bernstein: ''On dexterity and its development.'' *Journal of Motor Behavior,* **26,** 56–62.

Lerner, J. W. (1983). *Learning disabilities: Theories, diagnosis, and teaching strategies.* Boston: Houghton Mifflin.

Lezak, M. D. (1990). *Neuropsychological assessment.* New York: Oxford Univ. Press.

Maarse, F. J., Janssen, H. J. J., & Dexel, F. (1988). A special pen for an *XY*-tablet. In F. J. Maarse, L. J. M. Mulder, W. P. B. Sjouw, & A. E. Akkerman (Eds.), *Computers in psychology: Methods, instrumentation and psychodiagnostics* (pp. 133–139). Lisse: Swets and Zeitlinger.

Margolin, D. I., & Wing, A. M. (1983). Agraphia and microagraphia: Clinical manifestations of motor programming and performance disorders. *Acta Psychologica,* **54,** 263–283.

Meulenbroek, R. G. J., & Van Galen, G. P. (1988). The acquisition of skilled handwriting: Discontinuous trends in kinematic variables. In A. M. Colley & J. R. Beech (Eds.), *Cognition and action in skilled behaviour* (pp. 273–281). Amsterdam: Elsevier.

Miall, R. C., Weir, D. J., Wolpert, D. M., & Stein, J. F (1993). Is the cerebellum a Smith predictor? *Journal of Motor Behavior,* **25,** 203–216.

Mojet, J. W. (1991). Characteristics of the developing handwriting skill in elementary education. In J. Wann, A. M. Wing, & N. Søvik (Eds.), *Development of graphic skills* (pp. 53–75). London: Academic Press.

Portier, S. J., Van Galen, G. P., & Meulenbroek, R. G. J. (1990). Practice and the dynamics of handwriting performance: Evidence for a shift of motor programming load. *Journal of Motor Behavior,* **22,** 474–492.

Schmidt, R. A., Sherwood, D. E., Zelaznik, H. N., & Leikind, B. J. (1985). Speed–accuracy trade-offs in motor behavior: Theories of impulse variability. In H. Heuer, U. Kleinbeck, & K. H. Schmidt (Eds.), *Motor behavior: Programming, control, and acquisition* (pp. 79–123). Berlin: Springer-Verlag.

Schmidt, R. A., Zelaznik, H. N., Hawkins, B., Frank, J. S., & Quinn, J. T. (1979). Motor output variability: A theory for the accuracy of rapid motor acts. *Psychological Review,* **86,** 415–451.

Schoemaker, M. M. (1992). *Physiotherapy for clumsy children: An effect evaluation study.* Ph.D. Thesis, University of Groningen. Groningen: Stichting Kinderstudies.

Smits-Engelsman, B. C. M., Schoemaker, M. M., Van Galen, G. P., & Michels, C. G. J. (1996). Physiotherapy for children's writing problems: An evaluation study. In M. L. Simner, C. G. Leedham, & A. J. W. M. Thomassen (Eds.), *Handwriting and drawing research: Basic and applied issues* (pp. 227–240). Amsterdam: IOS Press.

Smits-Engelsman, B. C. M., Van Galen, G. P., & Portier, S. J. (1994a). Psychomotor Aspects of Poor Handwriting in Children. In: M. L. Simner, W. Hulstijn, & P. L. Girouard (Eds.), *Contemporary Issues in Forensic, Developmental, and Neurological Aspects of Handwriting* (pp. 17–44). Monograph of the Association of Forensic Document Examiners, 1, Toronto: Association of Forensic Document Examiners.

Smits-Engelsman, B. C. M., Van Galen, G. P., & Portier, S. J. (1991). Kinematic and cognitive features of handwriting development and proficiency. In G. E. Stelmach (Ed.), *Proceedings of the Fifth International Conference on Motor Control of Handwriting* (pp. 55–58). Tempe, AZ: Arizona State University.

Smits-Engelsman, B. C. M., Van Galen, G. P., & Portier, S. J. (1994b). Psychomotor development of handwriting proficiency: A cross-sectional and longitudinal study on developmental features of handwriting. In C. Faure, P. Keuss, G. Lorette, & A. Vinter (Eds.), *Advances in handwriting and drawing. A multidisciplinairy approach* (pp. 187–205). Paris: Europia Press.

Søvik, N. (1975). *Developmental cybernetics of handwriting and graphic behavior.* Oslo: Universitetsforlaget.

Teulings, H. L., & Maarse, F. J. (1984). Digital recording and processing of handwriting movements. *Human Movement Science,* **3,** 193–217.

Van Boxtel, A., & Schomaker, L. R. B. (1983). Motor unit firing rate during static contraction indicated by the surface EMG power spectrum. *IEEE Transactions on Biomedical Engineering,* **30,** 601–609.

Van Galen, G. P. (1991). Handwriting: Issues for a psychomotor theory. *Human Movement Science,* **10,** 165–191.

Van Galen, G. P., & De Jong, W. P. (1995). Fitts' law as the outcome of a dynamic noise filtering model of motor control. *Human Movement Science,* **14,** 539–572.

Van Galen, G. P., Portier, S. J., Smits-Engelsman, B. C. M., & Schomaker, L. R. B. (1993). Neuromotor noise and deviant movement strategies as an explanatory ground for poor handwriting in children. *Acta Psychologica,* **82,** 161–178.

Van Galen, G. P., & Schomaker, L. R. B. (1992). Fitts' law as a low-pass filter effect of muscle stiffness. *Human Movement Science,* **11,** 11–22.

Van Galen, G. P., Van Doorn, R. R. A., & Schomaker, L. R. B. (1990). Effects of motor programming on spectral density function of finger and wrist movements. *Journal of Experimental Psychology: Human Perception and Performance,* **16,** 755–765.

Van Galen, G. P., & Van Gemmert, A. W. A. (1996). Kinematic and dynamic features of forging another person's handwriting. *Journal of Forensic Document Examination,* **9,** 1–25.

Van Gemmert, A. W. A., & Van Galen, G. P. (in press). Stress, neuromotor noise and human performance: A theoretical perspective. *Journal of Experimental Psychology: Human Perception and Performance.*

Wann, J. P. (1987). Trends in the refinement and optimization of fine-motor trajectories: observations from an analysis of the handwriting of primary school children. *Journal of Motor Behavior,* **1,** 13–37.

Wann, J., & Kardirkamanathan, M. (1991). Variability in children's handwriting: Computer diagnosis of writing difficulties. In J. Wann, A. M. Wing, & N. Søvik (Eds.), *Development of graphic skills* (pp. 223–236). London: Academic Press.

Weinert, F., Simons, H., & Essing, W. (1966). *Schreibmethode und Schreibentwicklung* [Handwriting method and development]. Weinheim: Bletz.

Williams, H. G., & Woollacott, M. H., & Ivry, R. B. (1992). Timing and motor control in clumsy children. *Journal of Motor Behavior,* **24,** 165–172.

Wing, A. M. (1979). Variability in handwritten characters. *Visible Language,* **13,** 283–298.

Wing, A. M., Watts, F., & Sharma, V. (1991). Developmental dynamics of handwriting: Appraising the relation between handwriting and personality. In J. Wann, A. M. Wing, & N. Søvik (Eds.), *Development of graphic skills* (pp. 163–173). London: Academic Press.

RECEIVED: March 2, 1997; REVISED: June 27, 1997