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Quantitative Evaluation of Handwriting Skills during Childhood

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ABSTRACT

Background: Handwriting skills are very important skills for school-aged children, and consist of the abilities to control writing pressure and to assess shapes visually. Currently, various kinds of research have been conducted to clarify the developmental process of handwriting to establish methods for evaluating handwriting skills. However, a gold standard method has not been established. Purpose: This study aimed to clarify the developmental process of handwriting and to develop a new method for evaluating handwriting skills. Method: One hundred ninety-nine children aged from 4 to 12 years old and 17 young adults participated in this study. They were asked to draw a line carefully between two parallel lines with an electronic pen. Pressure during drawing and distance from the center point of the parallel lines were monitored continually using originally developed computer software. Results: Depending on age, the average pressure increased until seven years old, and afterward it was sustained at almost the same level as adults. The distance from the center points was similarly reduced until seven years old, and afterward it also remained at the same level. On the other hand, the time required for performance increased until the age of 7, whereupon it decreased with age. Considering the factor of speed in the second step, handwriting skills gradually improved depending on age even after seven years old. Conclusion: In the development of handwriting skills, our study suggests that accuracy develops in an earlier stage and then the ability of speed control develops in the next stage. The new method developed in this study is expected to be useful as a tool for evaluating handwriting skills. Our method might be useful in evaluating and supporting children with neurodevelopmental disorders, such as autism spectrum disorder, who are often affected by a lack of dexterity.

INTRODUCTION

Handwriting is an important skill for school-aged children (1-2). Handwriting skill consists of several factors, such as writing pressure, writing speed, and accuracy (3-5). Furthermore, the abilities of postural maintenance, control of muscle tension, coordination of the upper limbs, and eye movements influence handwriting skill (6-7). A number of studies on the relation between accuracy and speed have been reported. However, most previous studies have mainly focused on each individual factor.

There have been few studies that comprehensively estimated these multiple factors. Drawing speed and accuracy are closely related to the ability to control pressure in writing. The number of children who are suffering from developmental coordination disorder or unskillfulness has been increasing for several years (8-10). However, a standard method for evaluating handwriting skill has not been developed. The purposes of this study were to clarify how handwriting skills, including pen pressure, speed, and accuracy, change depending on age in children with typical development, and to develop a new method for evaluating handwriting skills.

MATERIALS AND METHODS

1) Participants

One hundred sixty-three children aged between 4 and 12 years old and 17 young adults aged from 19 to 22 years participated in this study (Table1). Children with disabilities, such as neurodevelopmental disorders, intellectual disability, or chronic diseases that might influence task completion, were removed from this study.

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2) Measurement of writing pressure and the distance from the center of the parallel lines

Writing pressure was measured using an electronic pen with a built-in writing pressure monitoring device, DP-1000/U (made by Nihon System Co., Ltd.). The assignment used was based on the maze assignment AGE BAND 1 of Movement Assessment Battery for Children Second Edition (11). Participants were instructed to draw a line carefully in the middle of two parallel lines. For writing pressure, the average of writing pressures while drawing the assignment was recorded every second using an electronic pen. The coefficient of variation (CV) of average writing pressure was calculated for comparing the degree of variation among different age groups. The lines drawn by participants were also recorded and the distance between the drawn lines and the center of the parallel lines was continuously measured by using originally developed computer software.

3) Accuracy score

The image of the lines that participants had drawn for the maze assignment was compared with the ideal image (a line that passed through the center of two parallel lines), and the score was calculated using the following formula (1)

$$Score = \frac{1}{IJ}\sum_{i=1}^{I}\sum_{j=1}^{J} X(i,j)M(i,j) \qquad (1)$$

where $X(i,j)$ is the pixel value of the i and j axis of the input image, and M(i, j) was the pixel value of the scoring mask image (the image is inverted black and white subtracting from the maximum brightness value 255). The scoring mask image was created using the following Gaussian function in our experiments.

$$M_g(i,j) = A(i,j) \otimes G(i,j) = \sum_m \sum_n A(m,n)G(m-i, n-j)$$

$$G(i,j) = \frac{1}{2\pi\sigma^2}\exp\left\{-\frac{(i-L/2)^2 + (j-L/2)^2}{2\sigma^2}\right\}$$

In the formula (1), high score points were gained when the line passed through near the frames, and score points were lost when the line went outside the frames. No points were gained or lost for lines drawn on the frames (points close to 0) in our experiments. We estimated the accuracy of drawing by using this score and defined it as accuracy score.

4) Completion time

The time required to draw the maze assignment was measured in each child. The time from the start to the finish was defined as completion time.

5) Method of analysis

Both the average writing pressure and the accuracy scores were analyzed. The average and the standard deviation of each age group were calculated, and the variance was analyzed. Then the average values of each age group were compared using Tukey's multiple comparison test. The relation between the average writing pressure and the accuracy scores were obtained using Spearman's correlation coefficient, and the relevance was analyzed. Furthermore, the relation between the time required for completing (completion time) and accuracy scores were obtained using Spearman's correlation coefficient, and the relevance was studied. In addition, we divided the accuracy score by the completion time, because the accuracy varies in inverse proportion to the time required. The significance level was set at less than 5%.

The statistical analysis was performed using IBM SPSS Statistics for Windows (version 19; IBM, Armonk, NY, USA) and Excel for Windows (version14.0; Microsoft, Redmond, WA, USA)

6) Ethical considerations

This study was approved by the Ethics Committee of Kobe University Graduate School of Medicine in accordance with the Helsinki Convention (approval number 236). Participants and guardians of participating children were informed of the purpose and contents of the study, both verbally and in writing, and they signed the consent form.

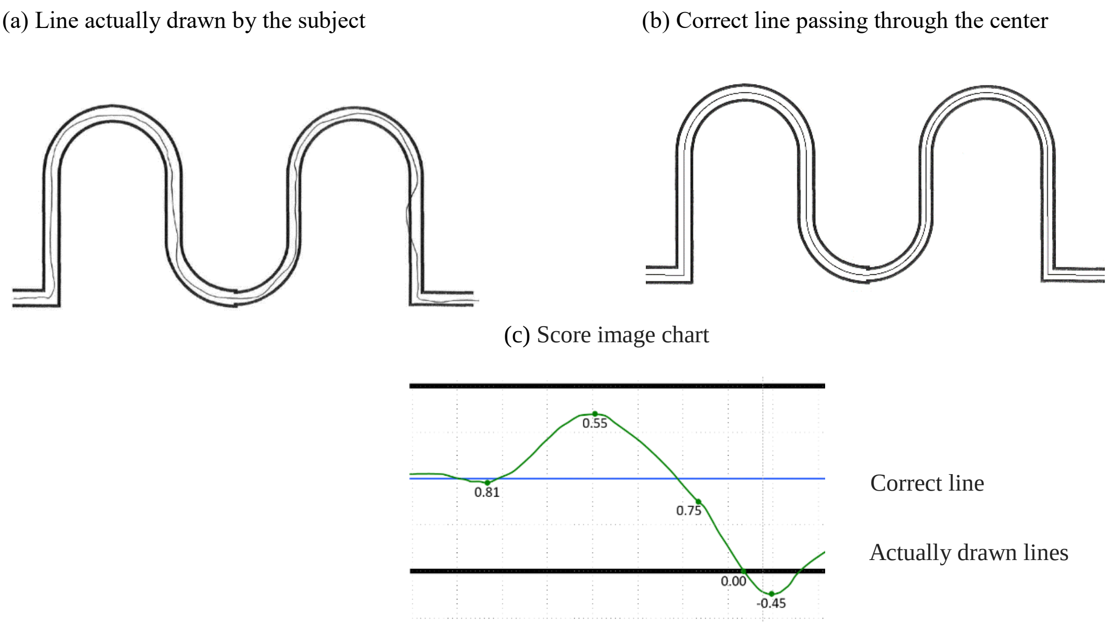

Figure 1. Principle of software used for calculating accuracy score

For the line drawing task, we created a new task based on the maze task in age band 1 of the Movement Assessment Battery for Children.

(a) An independently developed algorithm was used to calculate an "accuracy score": a continuous score representing how far the line drawn by each participant deviated from the center of the parallel lines.

(b)The accuracy score was calculated by comparing an image of the participant's line (Figure 1a) to an ideal image of a line passing through the center of the parallel lines.

(c)If it departed from the line, it was subtracted, and those scores were integrated.

RESULTS

1.Average writing pressure during drawing (Table I, II)

The results of analysis of variance (ANOVA) showed a significant main effect of the level in the average writing pressure during drawing. The results of multiple comparison tests showed that the 5 years old group showed a significantly lower value than the groups aged from 7 to 10 years. in the writing pressure value.

2. CV value of writing pressure during drawing (Table I)

No significant difference was observed in the CV value of writing pressure during drawing. However, there were no significant differences, the CV values of the groups of 4 and 5 years old were higher than the values of groups from 6 to 11 years old. The CV value showed a tendency to decrease with age until 6, whereupon it almost reached the same level as adults.

3. Completion time (the time required to complete the drawing task) (Table I)

Completion time showed a tendency to increase with age until 7, whereupon it decreased with age. There was no significant difference in the completion time among the different age groups.

4. Accuracy scores (Table I, II)

The values of accuracy score of the 4-year-old and 5-year-old groups were significantly lower than the groups from aged 6 to adult. ($p<0.05$ multiple comparisons analysis.)

5. Relationship of average writing pressure and accuracy scores

The relevance of the average writing pressure to accuracy scores was shown in figure 2. There was a positive correlation between the average writing pressure and accuracy scores ($r = 0.553$, $P<0.05$).

6. Accuracy scores / Completion time (Table I, II and Figure 3**)**

The accuracy scores were divided by the completion time, because it was well known that the accuracy varies in inverse proportion to the completion time. Accuracy score/completion time significantly increased by age. The developmental changes were shown in Figure 3.

Table I. Developmental change of five factors (mean pressure, CV value, accuracy score, completion time, accuracy score/completion time) by age.

Groups	n	Age	Mean pressure(g)	CV value	Accuracy score (points)	Completion time(sec)	Accuracy score /completion time (points/sec)
4 years	26	(4.3±0.5)	186.2±105.7	0.24±0.09	0.78±0.29	12.5±4.0	0.06±0.03
5 years	29	(5.2±0.6)	153.3±47.1	0.22±0.08	0.86±0.27	13.2±3.6	0.07±0.22
6 years	20	(6.3±0.5)	233.0±84.2	0.20±0.05	1.09±0.21	14.4±4.3	0.08±0.03
7 years	18	(7.2±0.4)	267.3±110.4	0.20±0.12	1.25±0.16	14.6±3.0	0.09±0.02
8 years	17	(8.2±0.4)	266.2±89.9	0.20±0.09	1.23±0.09	13.0±4.0	0.10±0.03
9 years	20	(9.1±0.3)	237.8±100.6	0.19±0.06	1.21±0.11	13.3±3.8	0.10±0.03
10 years	17	(10.3±0.6)	262.4±94.6	0.21±0.08	1.23±0.19	11.8±4.0	0.11±0.03
11 years	16	(11.2±0.4)	213.0±75.3	0.19±0.06	1.18±0.15	11.0±3.2	0.11±0.02
Adult	17	(19.7±0.6)	237.8±76.7	0.24 ± 0.13	1.13±0.15	12.0±3.9	0.10 ± 0.02

CV: coefficient of variation

Table II. Results of multiple comparison tests of three factors (mean pressure, accuracy score, accuracy score/completion time) associated with age.

	Multiple comparison test	
Mean pressure	5 years < 7 years – 10 years	P<0.05
Accuracy score	4 years, 5 years < 6 years – 11 years, adults	P<0.05
Accuracy score /completion time	4 years, 5 years < 8 years – 11 years, adults	P<0.05

The average values of each age group were analyzed by using a one-way analysis of variance and Tukey's multiple comparison test.

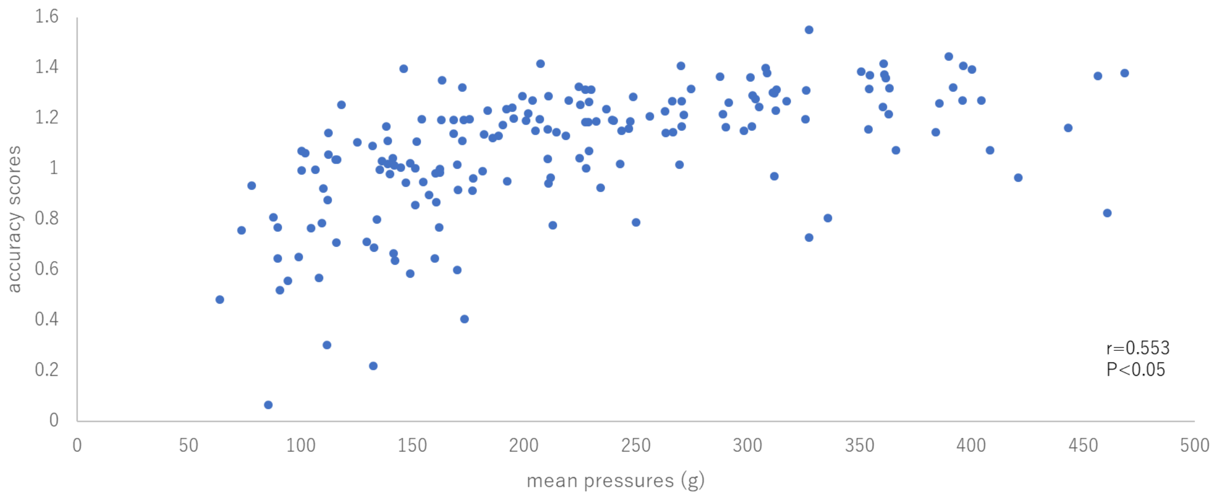

Figure 2. Relationship of the average writing pressure and accuracy scores.
Correlation between mean pressure and accuracy scores was analyzed by using Spearman`s correlation analysis.
N = 180 (P < 0.05) r =0.553 (r = Spearman`s coefficient)

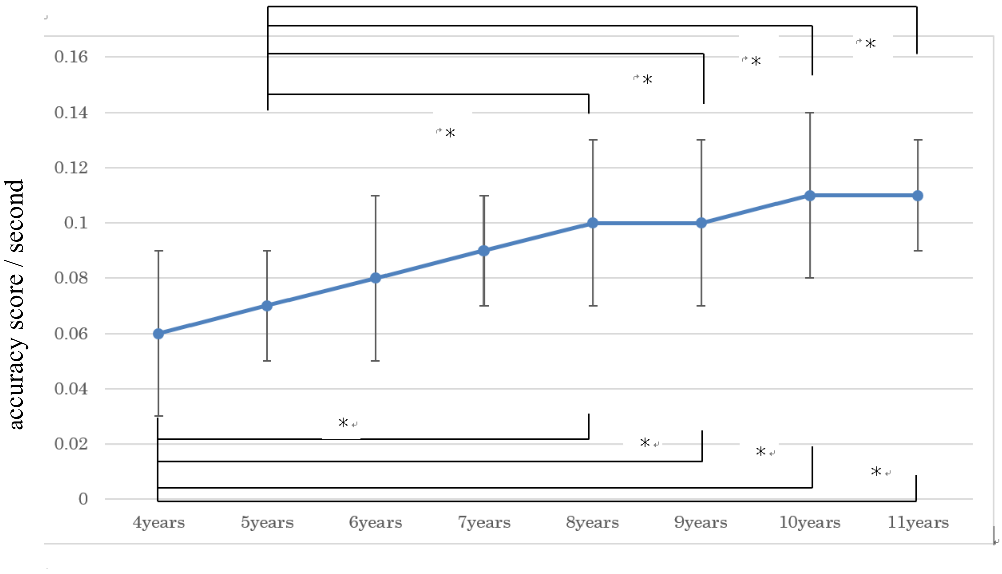

Figure 3. Accuracy score divided by completion time.
For comparison, one-way analysis of variance with no correspondence was performed. (Multiple comparisons analysis was completed to evaluate differences between age groups by using the Tukey-Kramer method. (*P < 0.05))

DISCUSSION

We quantitatively studied developmental changes in writing pressure by age. In our study, handwriting skills in typically developing children were quantitatively evaluated by using two new devices. One of the devices was an electronic pen, which was connected with a continuous monitoring system. As our electronic pen was very similar to an ordinary pen, participants could complete the task naturally. Our study showed that the average writing pressure was low at 5 years of age compared to 7-10 years in typically developing children. After seven years old, the writing pressure was almost the same as in adults. Moreover, the variation of measured value (CV) of writing pressure during performance decreased by age until six years old. It has been reported that depending on the development of hand skills and balance, the variation of the individuals in the same age group is reduced.(12) CV values in our study remained at almost the same constant level after seven years old. There have been few studies on the developmental change of writing pressure in children. Nakajima et al. compared the writing pressure of seven year old children with that of normal adults by using tablet PCs. They reported that seven year old children were unable to control writing pressure on the tablet as smoothly as adults (13). However, our result suggested that the ability of control in writing pressure mature a little earlier. In our study, the children drew the lines on paper, not on electronic tablets. The average of writing pressure was calculated from the data, and continuously monitored by an electronic pen device. When the children wrote the lines on the paper directly, they were able to feel the pressure more acutely. We considered that the participants could obtain feedback of sensory information from the pen more naturally. In our study, the average of pressure was obtained by continuous monitoring. We considered that the different measurement methods in our study produced different results from the previous study. We believe that our method in this study might detect developmental change more sensitively.

In addition, we developed original new software to quantify and estimate accuracy in this study. The results of our study suggested that the ability to control pen pressure was acquired by seven years old. Furthermore, we developed a system to evaluate writing skills from the accuracy of line drawing. The participants were ordered to draw a continuous line at the center of two parallel lines as quickly as they could. Their skills were estimated and scored by the distance from the center of two parallel lines. We called the score “accuracy score.”

The “accuracy score” increased until seven years old and maintained the same level. The accuracy at seven years old reached almost the same level as that of adults in our study. It was almost consistent with developmental changes in writing pressure. On the other hand, the time required for the performance increased until the age of seven, whereupon after seven years old it decreased with age. Considering the factor of speed in the second step, handwriting skills gradually improved depending on age even after seven years old.

Rosenblum reported that motion control functions develop from the ages of 4 to 11 (14 -15). Rueckriegel et al. reported that proximal joints such as the shoulder and elbow joints, were well controlled at seven years old, although the distal joints such as the hand and finger joints, require fine motion control and became more skillful with age (16). Tsuneishi also reported that the development of visual and tactile perception were important factors in utilizing tools and instruments (17). They also considered that visual perception could function well in combination with past memory and knowledge at six years old. In addition, the tactile sensory threshold was reported to reach almost the same level as that of adults at the ages of 5-6, and reached adult levels by the age of 9 (17).

The ability to control writing pressure and accuracy developed earlier in our study than in previous studies. However, when the factor of speed was accounted for, we obtained similar results to previous studies. Our results suggested that the various handwriting skills do not develop at the same time. In the first step, control of writing pressure and accuracy develops. Following the first step, the ability of control the speed matures in the next stage. We considered that the ability to draw lines accurately might be acquired along with the ability to adjust writing pressure. These abilities might be built based on visual perception and tactile function.

In general, accuracy varies in inverse proportion to the time required. Accuracy was reported to be influenced by the time for handwriting or line drawing (13). Baur et al reported that writing pressure at a normal speed was 1.4–1.5 N; however, the pressure increased in writing at high speed to a value of 1.7 N (3-4). Berwick et al. also reported that writing speed and accuracy are incompatible (5). These results are consistent with the results of our study. We considered that our results might have an important implication concerning the relationship between accuracy and speed. We divided the accuracy score by the time required for performance to clarify how accurately the lines were drawn in the fixed period. This value was considered to reflect the accurate performance rate per second, and the value increased with age until adulthood. As accuracy and speed were intimately related, when evaluating handwriting skills, these two factors should be included.

The number of children who suffer from autism spectrum disorder (ASD) is dramatically increasing worldwide (18). Children with ASD frequently suffer from developmental coordination disorder and clumsiness. Fuentes CT et al pointed out that children with ASD have specific handwriting deficits consisting of poor form, and that these deficits are predicted by their motor abilities (19). In addition, they revealed handwriting is still a problem in ASD through adolescence, and emphasized the importance of training (20). The new system that we developed is expected to help evaluating the handwriting skills and the degree of clumsiness in ASD children. The accuracy score might be applied for detection and training in children who are suffering from clumsiness and dyslexia.

When children engage in training handwriting skills, it is important to set up concrete goals. Furthermore, it is also essential for caregivers to know the effects of the training by score. Our method might be useful, not only to evaluate, but also to support children with neurodevelopmental disorders.

In our study, the number of participants was limited, and they belonged to kindergartens or elementary schools in the same area. In addition, it has been reported that hand skills and balance functions develop earlier in the female children than those in the male children, however, we could not analyze sex differences in this study mainly due to the limited number of participants,

We believe that future large scale studies will provide more detailed information about the development of handwriting skills in childhood.

CONCLUSION

In this study, we used two new methods to evaluate writing pressure, accuracy, and speed to clarify the development of handwriting skills in primary school children. Our study suggested that in handwriting skills, accuracy develops at an earlier stage and then the ability of speed control develops. In evaluating handwriting, we should pay attention to the three factors of writing pressure, accuracy, and speed. Our new evaluation method could be useful in evaluating handwriting skills in children suffering from neurodevelopmental disorders.

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