Haptic Guidance to Support Handwriting for Children with Cognitive and Fine Motor Delays

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Abstract—Handwriting is an essential skill for developing sensorimotor and intellectual skills in children. Handwriting constitutes a complex activity relying on cognitive, visual-motor, memory and linguistic abilities, and is therefore challenging to master, especially for children with learning difficulties such as those with cognitive, sensorimotor or memory deficits. Recently-emerged haptic guidance systems have a potential to facilitate the acquisition of handwriting skills in both adults and children. In this paper we present a longitudinal experimental study that examined the effects of haptic guidance to improve handwriting skills in children with cognitive and fine motor delays as a function of the handwriting complexity in terms of visual familiarity and haptic difficulty. A haptic-based handwriting training platform that provides haptic guidance along the trajectory of a handwriting task was utilized. 12 children with cognitive and fine motor delays defined in terms of intellectual difficulty (IQ score) and mild motor difficulty in pincer grasp control, participated in the study. Children were divided into two groups, a target group and a control group. The target group completed haptic-guided training and pencil-and-paper test whereas the control group took only the pencil-and-paper test without any training. A total of 32 handwriting tasks was used in the study where 16 tasks were used for training while the entire 32 tasks were completed for evaluation. Results demonstrated that the target group performed significantly better than the control group for handwriting tasks that are visually familiar but haptically difficult (Wilcoxon signed-rank test, $p < 0.01$). An improvement was also seen in the performance of untrained tasks as well as trained tasks (Spearman's linear correlation coefficient, 0.667; $p = 0.05$). In addition to confirming that haptic guidance can significantly improve motor functions, this study revealed a significant effect of task difficulty (visual familiarity and haptic complexity) on the effectiveness of haptic guidance for handwriting skill acquisition for children with cognitive and fine motor delays.

Index Terms—Haptic Interfaces, Evaluation/Methodology, Psychology, User-centered Design.

1 Introduction

Handwriting is a required skill in school that significantly influences child's academic and personal development [1]. The acquisition of handwriting skills starts at early childhood years (3–5 years old) and requires several years of formal training to master [2]. Learning handwriting improves fine motor skills [3] and general language acquisition [4] [5]. Research suggests that the benefits of teaching handwriting go beyond simply writing [4]; there is increasing evidence of a link between the fine motor skills required in handwriting and the development of cognitive skills that improve readability and comprehension. Research also suggest that the process of forming letters while handwriting activates neural pathways that are associated with strong reading/-comprehension skills [5].

Mastering handwriting involves a complex blend of sensorimotor, perceptual, cognitive, and linguistic skills. The acquisition of handwriting skills is a physical, repetitive, and time-consuming task that demands significant cognitive and physical efforts. The population of children with learning difficulties, such as intellectual, sensory or motor disabilities, is noticeably increasing across the globe [6] [7]. Children with learning difficulties require comprehensive care and innovative interventions especially during the early childhood years [6]. Teachers do not have enough resources to teach handwriting to students with learning difficulties as it involves personalized one-on-one interventions [8].

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Assistive technologies can supplement teacher's efforts to improve learning outcomes for children with learning difficulties [9]. Contemporary technologies such as graphics tablets, which emulate writing with a stylus on a digital surface, with dedicated software to provide interactive audio-visual feedback based on the learner's performance [10]. Inspired by pedagogical theories such as the peer-tutoring or learning-by-teaching method [11], social robots play the role of a teacher or a peer learner in order to improve learning outcomes [12]. Recent studies demonstrated that Augmented Reality (AR) technology also has the potential to improve learning outcomes for handwriting skills acquisition [13].

The majority of currently-available handwriting learning technologies engage auditory and visual modalities in the learning process [14]. However, generation of complex handwriting requires not only perceptual and cognitive skills, but also the ability to process proprioception (kinesthetic) and tactile information [15]. Previous studies showed a high level of correlation between fine motor skills and handwriting legibility [16]. For instance, fine motor skills such as fine motor precision, manual dexterity, and in-hand manipulation allow for the demonstration of good handwriting legibility [17]. The newly-emerged haptic tech-

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nologies demonstrate very promising results in developing motor skills in children [18], and thus have great potential to improve the acquisition of handwriting skills. For example, force feedback guidance methods are proposed to improve motor functions such as medical training [19], tele-operation [20], rehabilitation [21], and education [22].

2 Related Work

Haptic-based assistive systems engage the human sense of touch in the learning process by physically controlling/guiding the hand movement along a desirable trajectory via a haptic interface [23]. Even though some studies examined the effects of vibrotactile feedback to improve handwriting skills [24], the majority of research in haptic-based handwriting learning systems involved force feedback guidance [2] [22] [25] [26]. Force feedback guidance, commonly used in motor training tasks, refers to forces generated by a haptic interface to physically guide a user through a desired trajectory of movement. For instance, haptic guidance has been used to record an expert's movements and play it back for novice learners in order to facilitate the acquisition of handwriting skills [27].

Early studies focused on investigating the feasibility of haptic-based handwriting learning for teaching adults Japanese characters [28], [29], Chinese characters [30], Latin alphabet letters [25] [31], Persian calligraphy [32], and Jawi alphabet letters [33]. For instance, a haptic calligraphy system for Japanese characters used two displays, one for the teacher and one for the student [28]. Using the teacher's traces of letters and force trajectories as a reference for the student, results showed that as the exercise was repeated, the students' letters resembled better those of the teacher's. Recent studies explored different types of haptic guidance, such as full, partial, and disturbance guidance to enhance handwriting skills acquisition with adult learners [34]. Results demonstrated that partial haptic guidance is more effective at the early stages of handwriting learning (since it allows the acquisition of gross motor skills essential for handwriting) whereas full haptic guidance was more effective at intermediate/advanced stages of the learning process (as full haptic guidance improved fine motor skills) in the case of adults learning a new language.

Haptic guidance for teaching children handwriting skills has also been explored. In one work, the effectiveness of virtual calligraphy teaching by measuring the time and velocity of the subjects' movements is examined [25]. The experimental study with 22 six-year-old children showed an improved handwriting performance, indicated by the increased fluency in movements and decreased values of velocity peaks. A subsequent study examined different force-feedback guidance methods for typical children and demonstrated that pupils performed statistically better with partial haptic guidance compared to full haptic guidance (performance was evaluated based on fluency and regularity of handwriting) [35]. Results demonstrated that partial/disturbance guidance is more effective for teaching gross motor skills while full guidance is more effective for fine motor skills. A similar conclusion is reported with adults [34].

There has been interest in using haptic feedback for teaching children with different learning difficulties. For example, one study [36] applied the robotic haptic interface, incorporating proprioceptive feedback into maze exploration, to improve handwriting in children experiencing challenges with eye-hand coordination. Another study [37] provided a qualitative investigation of haptic games for improving integration of visual skills and motor skills, in children experiencing a wide range of learning disabilities. According to [37], the introduction of haptic technology in occupational therapy has a positive effect on childrens' interest and involvement in haptics-based educational games. Other haptic-based systems were proposed for teaching handwriting for children with learning difficulties [38] [39]. In another study [40], a haptics-assisted system based on two haptics devices (Phantom Omni™ versus Novint Falcon™) was tested on typical children and those with learning difficulties. In all groups the performance of tracing handwriting task increased, with typical children demonstrating higher precision and lower variance compared to their peers with learning difficulties.

Existing work has focused on studying the effects of various haptic guidance techniques with little emphasis on the relationship between task complexity/familiarity and performance. Furthermore, previous studies focused on short-term effectiveness of haptic guidance. In our previous works, we developed a longitudinal study with typical children to study the effects of haptic guidance as the task complexity increases [35]. In addition, we conducted a pilot study to develop a method based on traditional copy work to assess the handwriting quality in children with learning difficulties based on the visual familiarity and haptic complexity of the handwriting task, including characters, numbers, shapes, and emoticons [41]. In the current study, we conducted a 9-weeks longitudinal experiment to examine how the visual familiarity and haptic complexity of the handwriting task influences the effectiveness of haptic guidance for the acquisition of handwriting skills for children with cognitive and fine motor delays. Four levels of handwriting tasks were considered: visually familiar and haptically low difficulty; visually familiar and haptically medium difficulty; visually familiar and haptically high difficulty; and visually unfamiliar and haptically high difficulty.

3 Methods

3.1 Experimental Apparatus

The experimental setup was similar to the one proposed in our previous work [35]. The Novint's Falcon haptic device [42] is used with a stylus-shaped custom grip to provide 3 DoF force feedback guidance. A seven-inch touchscreen mounted under the stylus served as the writing surface. The setup is shown in Figure 1. The haptic interface was calibrated with the touchscreen device to provide an accurate correspondence between the stylus tip's movement and the displayed shape. To improve the fidelity of the haptic guidance force, a custom grip is designed to firmly attached the pen-like stylus to the haptic device and enhance the coupling between the stylus and the haptic device. The platform has been calibrated for children with learning difficulties. With the help of the physiotherapist, the calibration process involved reducing the magnitude of haptic guidance force,

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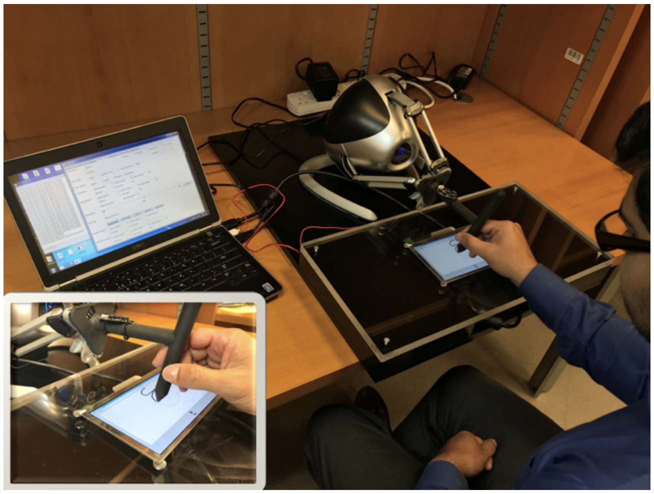

Fig. 1: Novint's Falcon™ haptic device used in experiments. The children grab the pencil-shaped end effector and the haptic device guides the participants' handwriting to know how to write the task letter or draw task shape.

the haptic guidance speed, and allowing larger error margin before activating the haptic guidance.

3.2 Haptic Guidance

Three approaches for haptic guidance are common to support handwriting, namely full (or proactive) guidance, partial (or retroactive) guidance, and disturbance guidance [35]. Knowing that kinesthesis (sense of position and movement) plays a significant role in haptic training as it provides the information pathway for the perception of incoming stimuli [22], full haptic guidance was utilized for this study.

In the full haptic guidance approach, the haptic interface takes the leading role in the handwriting trajectory whereas the learner follows the trajectory through the visual and/or haptic guidance. Once the learner moves the stylus to the starting point of the handwriting task, the haptic guidance method is activated. The algorithm retrieves the next position along the handwriting trajectory, calculates the force to move the stylus to the next position, and renders the force using the haptic device. The force is calculated in accordance with equation 1. Once the stylus is within a close proximity of the target position, the following position is picked and a new force is calculated and rendered. A summary of the haptic guidance method is shown in algorithm 1.

Algorithm 1 Full haptic guidance method.

```
while #_of_points>0 do
    if ||Target_Pos − Current_Pos||_L2 < ϵ then
        Read_Next_Position(Target_Pos)
        #_of_points = #_of_points - 1;
        Calculate_Force(Target_Pos)
    else
        blink_Dot(Target_Pos)
    end
    Render_Force(Force)
end
```

$$F(t) = K_{max}\Delta u \quad (1)$$

where K_{max} is the maximum stiffness of the haptic interface and Δu is the point-to-point displacement.

3.3 Participant Background

22 children with cognitive and fine motor delays from different schools in Abu Dhabi were initially recruited for this study (11 for treatment group and 11 for control group). The inclusion criteria were the following: (1) children with age range 4-9 years old, (2) children with mild intellectual difficulties (60.5-73 IQ score as evaluated through the WISC-V [43] [44] and WPPSI-III [45] [46] IQ assessment standards) - note that children with lower IQ could not handle the experiment task while children with higher IQ found it too easy, (3) children with mild fine motor control difficulty over their pincer grasp (the coordination of the index finger and thumb to hold an item), and (4) children who are right-handed and have no occupational problems. The study was approved by the Institutional Review Board for Protection of Human Subjects in the American Center for Psychiatry and Neurology (Project # 0017) and New York University Abu Dhabi (Project # 101–2016).

The participants had to be examined by a clinical psychologist for inclusion in the study. The examinations were performed at the American Center of Psychiatry and Neurology in Abu Dhabi, UAE. The two IQ tests are designed to measure intellectual ability consisting of verbal comprehension, visual spatial, fluid reasoning index, working memory, and processing speed. The IQ scores are reported with corresponding ranges at the 95% confidence level, meaning that it can be said with 95% certainty, that scores fall within the ranges stated. The results of the children assessment have not been disclosed as per the policy of the clinic.

A total of 10 children were excluded from the analysis due to the following reasons: (1) side bias, (2) failure to reach the test phase due to lack of attention, or (3) failure to complete at least 50% of the test trials due to multiple absences. Therefore, the analysis is conducted with data from 7 participants in the treatment group (5 male, mean age of 7 $\pm$ 1.53 years) and 5 participants in the control group (5 male, mean age of 5.5 $\pm$ 1.00 years).

3.4 Experimental Protocol

The children visited once a week to participate in the experiment for a longitudinal total lasting for nine weeks. Before the experiment started, every participant completed a paper-based copy test. Participants were then assigned to the treatment or the control group by considering the balance of gender, age, and similarity score of the paper-based copy test. There were 11 participants in the treatment group (7 male, mean age of 6.67 $\pm$ 1.5 years, similarity score was 19.37 $\pm$ 1.62) and 11 participants in the control group (8 male, mean age of 6.3 $\pm$ 1.57 years, similarity score was 20.94 $\pm$ 1.5). Before starting the longitudinal experiment, it was confirmed that there were no significant differences in gender, age and similarity score between the control and treatment groups based on the 32 paper-based copy tasks. The sheet of the paper-based copy task is shown in Figure

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TABLE 1: Tasks grouped according to the familiarity and haptic difficulty levels based on the similarity between reference and copy scores. The tasks used for training the target group are marked with *.

Visual	Familiar			Unfamiliar
Haptic	Low	Medium	High	High
	i	2	⇨*	6
	s*	3*	☆	٨
	△*	5*		٩
		٤*		k*
		٣*		ك
		p		♡
		د*		⯃
		ب		▱
		ظ*		😎*
		◠*		☹*
		▭*		😢
		☺		😵
		😟*		
		😄*		
		☺		

3 (appendix page). We also used the same sheet for the evaluation of the participants' handwriting improvement.

To assess handwriting and fine motor skills, we created a paper-based copy sheet (appendix page) of tasks of different levels of visual familiarity and haptic difficulty. The handwriting tasks consisted of eight handwriting tasks from four different classes including numbers, shapes, letters, and emoticons, and various difficulty levels within each category, for a total of 32 handwriting tasks. All children lived in an Arabic and English-speaking community, therefore, handwriting tasks from Arabic and English were included in the study (letters/numbers), in addition to shapes and emoticons. The 32 handwriting tasks were analyzed and classified into one of the four categories, visually familiar and haptically low difficulty, visually familiar and medium haptic difficulty, visually familiar and haptically high difficulty, and visually unfamiliar and haptically high difficulty, based on the method proposed in [41]. The handwriting tasks were analyzed based on two types of properties in handwriting production: morphokinetic (shape of the letter) and topokinetic (spatial/temporal properties of the handwriting trajectory). The morphokinetic properties were utilized to determine the visual familiarity of the handwriting task whereas the topokinetic properties described the haptic difficulty. The result of the classification is shown in Table 1. Training items were selected so that the average difficulty between trained and untrained tasks were as close as possible to maintain balanced grouping.

The treatment group completed two training sessions separated by 40 minutes break during every visit. To keep children from losing interest in participating in the experiment, a break time was offered to participants within the training session. During the training session, participants completed 16 handwriting tasks (marked with * in Table 1) for three times each. At the end of every visit (two training sessions), participants completed the paper and pencil test for all 32 handwriting tasks. The total training time of one session is 10–20 minutes depending on the participants' cooperation. The control group took the paper-based copy test once a week without any training. After the paper-based test, participants were rewarded with a sticker. All students in the treatment and control groups are expected to be exposed to numbers, letters, shapes, and emoticons in their daily life and in school, and some learning effects may have taken place. This exposure and learning factor is extremely difficult to control. However, it is assumed that such exposure and learning would be similar for both groups since all participants were recruited from the same learning center. Handwriting skills can be improved by these nine weeks of exposure and repeated paper-based tests. The control group served as a baseline where the improvement of the treatment group were dominantly based on haptic training.

3.5 Handwriting Evaluation and Data Analysis

The participant's handwriting was evaluated by grading the paper and pencil test for the 32 copy tasks on a scale of 0 to 100 points. Given the sizable intra-rater and inter-rater levels of disagreement in evaluating handwriting tasks for children with learning difficulties [47] (such as the BHK test for disgraphia [48]), two experts were recruited. The handwriting experts were specialized clinical psychologists with more than 10 years of experience teaching handwriting skills for children with learning difficulties. The students' information and the number of visits were blinded, and the experts evaluated with unique numbers of randomly mixed sheets. Inter-rated reliability analysis showed a fair agreement between the scores of the two experts (Kappa coefficient was 0.26). The handwriting tasks were evaluated on a scale between 0 (totally wrong handwriting) and 100 (perfect handwriting). The evaluation metrics were (1) similarity between reference and copy (50 points weight), (2) size and position (30 points weight), and (3) fluency (line continuity, 20 points weight). All statistical analysis results presented in this study are based on the average scores from the two experts evaluations.

It is worth noting that as children with cognitive and fine motor delays often experience behavior problems such as reduced self-confidence or increased anxiety and stress [49], there had been noticeable differences in their performance from day to day. In addition, several participants were absent during the longitudinal study period. Thus, the data was pre-processed in order to remove outliers and fill data gaps. To detect outliers, 1.5 of interquartile range (IQR) was used as a criterion. The detected outlier/missing value was replaced with a value obtained by linear interpolation of two neighboring points or linear extrapolation when the outlier/missing value was at the beginning or the end of the interval. On average for both target and control groups the number of outliers were around 7.4% of the total data. All scores for each participant and for each task for all nine weeks were processed. Then the average for each group are calculated for the 9 weeks, for the four types of handwriting tasks: visually familiar, haptically low difficulty (VFHL), visually familiar, haptically medium difficulty (VFHM), visually familiar, haptically high difficulty (VFHH), and visually unfamiliar, haptically high complexity (VUHH). A third degree polynomial regression was used to visualize the learning curves over time.

In order to assess the differences between the target and control groups, the non-parametric Wilcoxon signed rank test was used since the data is not normally distributed and that has limited sample size.

4 Results

Comparisons were drawn between the target and control groups over the course of 9 weeks for the four types of handwriting tasks, in order to study the effects of haptic guidance on progressing the development of handwriting skills for children with cognitive and fine motor delays. The improvement rate was calculated as shown in equation 2.

$$\text{rate}_w = \frac{S_w - S_0}{50 - S_0} \cdot 100, \quad (2)$$

where rate_w is an improvement rate for week w (in %), S_w a similarity between reference and copy score for week w, S_0 is the score for the first week taken as a reference and 50 is the upper margin of the similarity between reference and copy score (S-score).

As shown in Figure 2, haptic guidance plays a crucial role in improving the development of handwriting skills, particularly for specific types of handwriting tasks. First of all, the quality of handwriting for both the target and the control groups show a steady increase for visually familiar and haptically easy handwriting tasks (as shown in Figure 2a), although with no statistical significance for both groups. It is also worth noting that there was no statistically-significant difference between the control and target group for this type of handwriting tasks. It can be concluded that for visually familiar and haptically easy handwriting tasks, haptic guidance may not play a crucial role in improving the quality of handwriting. This finding explains why unimodal visual feedback was dominantly applied for simple handwriting tasks [50].

It is interesting to find that the improvement in handwriting was statistically better for the control group, compared to the target group, for the visually familiar and haptically medium difficulty tasks (VFHM), as shown in Figure 2b (Wilcoxon signed-rank test, $p < 0.01$). It seems for medium complexity haptic tasks, haptic feedback may have a negative effect on learning. This is in line with previous findings that concurrent augmented feedback is less effective for learning simple motor tasks, compared to complex ones [51].

For the visually familiar and haptically high difficulty tasks (VFHH), the improvement for the target group was statistically better than that of the control group (Wilcoxon signed-rank test, $p < 0.01$). Therefore, for visually familiar but haptically difficult tasks, haptic guidance seems to play a crucial role in improving learning outcomes. This is in line with previous findings that concurrent haptic feedback fosters complex motor task learning [52], and seems to be true for haptically complex handwriting skills. Furthermore, in an attempt to demonstrate that the improvement in handwriting is actually a result of learning and not due to short-term memory effects [53], the data from the 16 handwriting tasks that participants in the target group never trained with was analyzed and compared to the 16 handwriting tasks that were used for training. As shown in Table 1, third column, the arrow (⇨) task was used for training while the arrow (⇨) and star (☆) tasks were used for evaluation. Comparison of the handwriting improvement curves revealed similar learning effects not only in the trained tasks, but also in the untrained tasks (Spearman's rank correlation coefficient ρ = 0.66, p=0.05).

Finally, for the visually unfamiliar and haptically challenging tasks, Figure 2d shows no significant improvement in the control and target groups. That is backed by the challenge point theory [54], stating that novice or less experienced learners may not improve if the task is too challenging. It is clear that, for this type of handwriting tasks, other intervention techniques must be utilized as haptic guidance may not be an effective one (other methods of haptic guidance would be interesting to examine).

In summary, haptic guidance significantly improved handwriting skills development for tasks that are visually familiar but haptically hard (Figure 2c). However, haptic guidance did not show any significant improvement for handwriting tasks that are haptically difficult and visually unfamiliar. Therefore, it may be concluded that haptic guidance is significantly effective for handwriting tasks that are difficult to write despite being visually familiar.

5 Discussion

In summary, it is found that children with cognitive and fine motor delays benefit most from haptic guidance when learning handwriting tasks that are visually familiar but difficult to reproduce haptically. For visually-familiar tasks of medium difficulty, no significant improvement was detected. We hypothesize, that in case of visually familiar shapes such as **i** (one stroke and a dot) and **s** (a wavy line), passive learning is taking place, i.e. children just following the corrective force without making efforts to improve their skills. Furthermore, children also did not demonstrate any significant progress in acquiring handwriting skills while performing visually unfamiliar and haptically difficult tasks. The presence of an unfamiliar shape in handwriting task necessitates an allocation of additional working memory resources to remember and reproduce. Therefore, significant cognitive effort and integration of visual-motor skills are required to follow the trajectory of haptically challenging task, even with the corrective force guidance. Given the challenges the children with cognitive and fine motor delays face in integrating, organizing, and planning visual information to control their pincer grip, it is reasonable to assume that reproducing the complex trajectory of a handwriting task might be confined by these

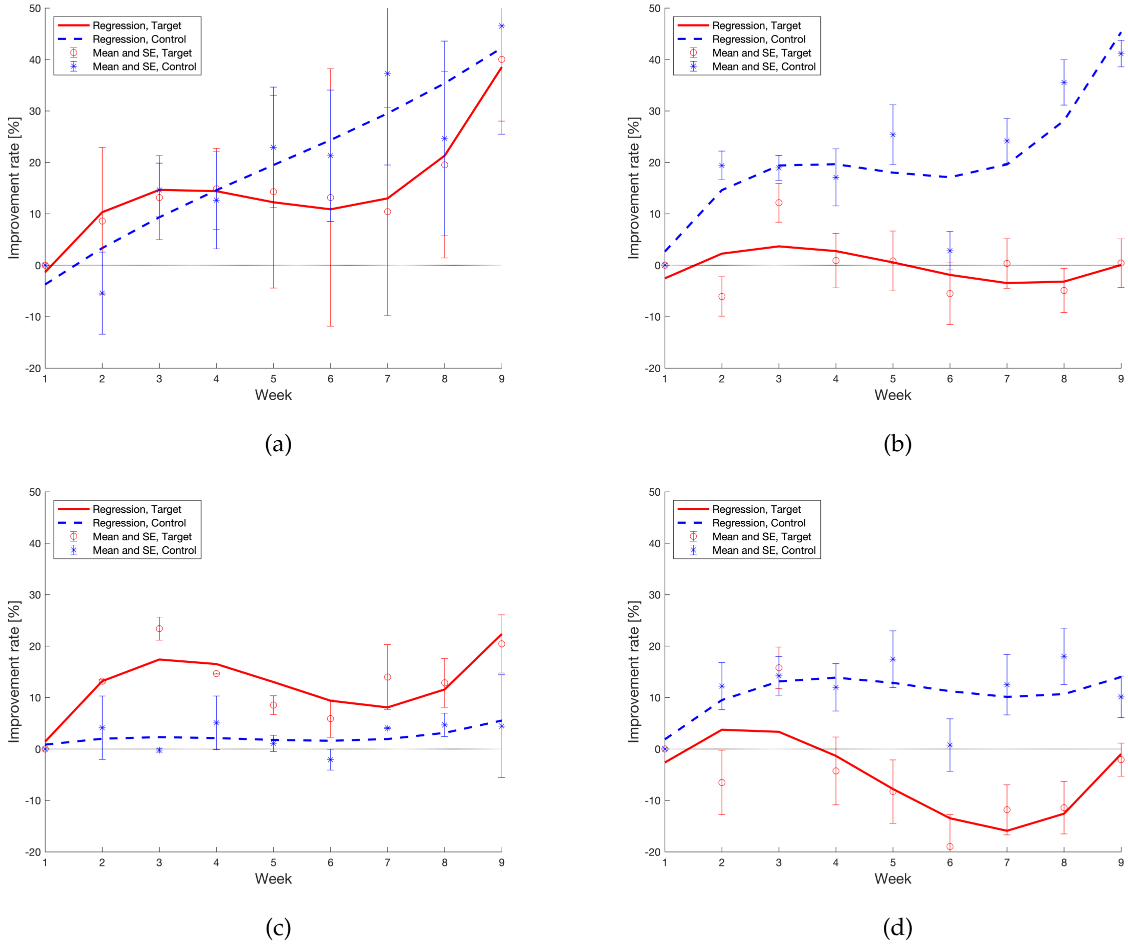

Fig. 2: (a) Visually familiar and haptically low difficulty tasks (VFHL); (b) Visually familiar and haptically medium difficulty tasks (VFHM), learning curves are significantly different, Wilcoxon signed-rank test, $p < 0.01$; (c) Visually familiar and haptically high difficulty tasks (VFHH), learning curves are significantly different, Wilcoxon signed-rank test, $p < 0.01$; (d) Visually unfamiliar and haptically high difficulty tasks (VUHH). Solid and dashed lines are 3rd order polynomial regression of original improvement rate. SE indicates standard error.

limitations. Overall, using haptic guidance for children with cognitive and fine motor delays seems to improve motor skills in tasks that do not require significant processing of the visual properties of the task.

It is interesting to examine improvement in handwriting for the two groups across the four types of handwriting tasks. Even though graphs show monotonic increase (Figure 2a), it was found that for VFHL tasks, there was no statistical significance in the quality of handwriting after 9 weeks. This could be due to the low sample size obtained for this group. As for the VFHM tasks, the improvement for the target group was not significant despite the training sessions whereas the control group had significant improvement (Wilcoxon signed-rank test, $p < 0.01$).

When learning involves both cognitive and motor systems, as is the case with handwriting skills, there is a bidirectional interaction between cognition and action. This interaction has been demonstrated in the area of embodied cognition [55]. For instance, visual representations of handwriting tasks are linked to motor representation, where neuroimaging research demonstrated that visual handwriting perception recruits motor systems that are usually dedicated to executing a handwriting task [56]. Some studies with young children have shown that overt, rather than just passive, motor action further enhances letter perception [57]. The effectiveness of haptic guidance seems to be explained through this interaction between cognition and motor systems where haptic guidance stimulates the the motor system which eventually influences cognitive learning.

Even though the task completion time was included in the performance analysis in previous studies involving typical children [35], the handwriting experts were strongly opinionated against using the task completion time to evaluate performance for children with learning difficulties. Therefore, the task completion time was not recorded.

Although findings in this study were supported by statistical significance, a few limitations should be mentioned. First of all, it must be noted that the recruited children had different learning difficulties (cognitive and fine motor delays). We anticipate the results might be slightly different if participants had the same specific learning difficulty, such as dysgraphia. Another limitation stems from the missing data points during this longitudinal study caused by the absence of some of the participants or lack of sufficient cognitive attention while performing the handwriting tasks. Initially, 22 participants were recruited, however, data from 10 participants have to be dropped due to various reasons. For instance, there were cases in which participation was completely abandoned if the student was absent for several training sessions due to personal matters. There were also challenges while handling the participants, for example children completed the task without proper cognitive attention or without showing sufficient involvement. All these circumstances influenced the data collection process.

6 Conclusion

In this paper we presented a longitudinal study, aiming to investigate the effect of haptic guidance in teaching handwriting to children with cognitive and fine motor delays as a function of the complexity of the handwriting task in terms of visual familiarity and haptic difficulty. Results demonstrated that the effectiveness of haptic guidance depends largely on the type of handwriting tasks. It was shown that haptic guidance significantly improves motor function of the handwriting skill for children with cognitive and fine motor delays when the task is visually familiar and haptically difficult. However, haptic guidance did not show any significant improvement, and results in even worse performance, for tasks that involve low to medium motor complexity and for tasks that are visually unfamiliar.

As for future work, we would like to focus on a specific learning difficulty such as children with attention difficulties, dysgraphia, dyspraxia, or processing deficits. Furthermore, different haptic guidance methods such as partial and disturbance haptic guidance will be examined for each learning difficulty. For instance, it would be interesting to find if disturbance haptic guidance would improve handwriting acquisition for children with attention difficulties. The work reported here paves the way for such studies. Finally, we plan to examine the effectiveness of haptic guidance across different age groups.

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References

[1] K. Feder, A. Majnemer, and A. Synnes, "Handwriting: Current trends in occupational therapy practice," *Canadian Journal of Occupational Therapy*, vol. 67, no. 3, pp. 197–204, 2000.

[2] C. S. Puranik and C. J. Lonigan, "From scribbles to scrabble: Preschool children's developing knowledge of written language," *Reading and writing*, vol. 24, no. 5, pp. 567–589, 2011.

[3] J. Ziviani and J. Elkins, "Fine motor skills in the classroom," in *Down Syndrome*. Springer, 1993, pp. 135–150.

[4] L. H. Dinehart, "Handwriting in early childhood education: Current research and future implications," *Journal of Early Childhood Literacy*, vol. 15, no. 1, pp. 97–118, 2015.

[5] K. James and V. Berninger, "Brain research shows why handwriting should be taught in the computer age," *LDA Bulletin*, vol. 51, no. 1, pp. 25–30, 2019.

[6] V. C. Alfonso and D. P. Flanagan, *Essentials of specific learning disability identification*. John Wiley & Sons, 2018.

[7] H. L. Swanson, K. R. Harris, and S. Graham, *Handbook of learning disabilities*. Guilford press, 2013.

[8] S. Graham, K. R. Harris, L. Mason, B. Fink-Chorzempa, S. Moran, and B. Saddler, "How do primary grade teachers teach handwriting? a national survey," *Reading and writing*, vol. 21, no. 1-2, pp. 49–69, 2008.

[9] D. Maor, J. Currie, and R. Drewry, "The effectiveness of assistive technologies for children with special needs: a review of research-based studies," *European Journal of Special Needs Education*, vol. 26, no. 3, pp. 283–298, 2011.

[10] F. Coutinho, M.-E. Bosisio, E. Brown, S. Rishikof, E. Skaf, X. Zhang, C. Perlman, S. Kelly, E. Freedin, and N. Dahan-Oliel, "Effectiveness of ipad apps on visual-motor skills among children with special needs between 4y0m–7y11m," *Disability and Rehabilitation: Assistive Technology*, vol. 12, no. 4, pp. 402–410, 2017.

[11] S. Bloom, *Peer and cross-age tutoring in the schools: an individualized supplement to group instruction*. US Department of Health, Education, and Welfare, National Institute of Education, 1976.

[12] S. Chandra, P. Dillenbourg, and A. Paiva, "Children teach handwriting to a social robot with different learning competencies," *International Journal of Social Robotics*, pp. 1–28, 2019.

[13] N. F. S. Jeffri and D. R. A. Rambli, "Design and development of an augmented reality book and mobile application to enhance the handwriting-instruction for pre-school children," *Open Journal of Social Sciences*, vol. 5, no. 10, pp. 361–371, 2017.

[14] S. O. Chicu, A. Ţicău, and L. Şoitu, "Training for new technologies. handwriting with new technologies," *Procedia-Social and Behavioral Sciences*, vol. 142, pp. 781–785, 2014.

[15] F. Bara and E. Gentaz, "Haptics in teaching handwriting: The role of perceptual and visuo-motor skills," *Human movement science*, vol. 30, no. 4, pp. 745–759, 2011.

[16] S.-M. Seo, "The effect of fine motor skills on handwriting legibility in preschool age children," *Journal of physical therapy science*, vol. 30, no. 2, pp. 324–327, 2018.

[17] J. Alston and J. Taylor, *Handwriting: Theory, research and practice.* ERIC, 1987.

[18] M. Eid, M. Orozco, and A. E. Saddik, "A guided tour in haptic audio visual environments and applications," *Int. J. Adv. Media Commun.*, vol. 1, no. 3, p. 265–297, Jun. 2007. [Online]. Available: https://doi.org/10.1504/IJAMC.2007.013918

[19] T. R. Coles, D. Meglan, and N. W. John, "The role of haptics in medical training simulators: a survey of the state of the art," *IEEE Transactions on haptics*, vol. 4, no. 1, pp. 51–66, 2010.

[20] M. Selvaggio, P. R. Giordano, F. Ficuciellol, and B. Siciliano, "Passive task-prioritized shared-control teleoperation with haptic guidance," in *2019 International Conference on Robotics and Automation (ICRA)*. IEEE, 2019, pp. 430–436.

[21] S. A. Ali, M. F. Miskon, A. Shukor, M. B. Bahar, and M. Q. Mohammed, "Review on application of haptic in robotic rehabilitation technology," *Int J Appl Eng Res*, vol. 12, no. 12, pp. 3203–3213, 2017.

[22] D. Feygin, M. Keehner, and R. Tendick, "Haptic guidance: Experimental evaluation of a haptic training method for a perceptual motor skill," in *Proceedings 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. HAPTICS 2002*. IEEE, 2002, pp. 40–47.

[23] M. A. Eid, M. Mansour, A. H. El Saddik, and R. Iglesias, "A haptic multimedia handwriting learning system," in *Proceedings of the international workshop on Educational multimedia and multimedia education*. ACM, 2007, pp. 103–108.

[24] D. Babu, H. Nagano, M. Konyo, and S. Tadokoro, "A new approach for realistic vibrotactile friction feedback for midair writing systems." in *The Proceedings of JSME annual Conference on Robotics and Mechatronics (Robomec) 2016*. The Japan Society of Mechanical Engineers, 2016, pp. 1A2–19b1.

[25] R. Palluel-Germain, F. Bara, A. H. de Boisferon, B. Hennion, P. Gouagout, and E. Gentaz, "A visuo-haptic device - telemaque - increases kindergarten children's handwriting acquisition," in *Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)*, March 2007, pp. 72–77.

[26] J. Guilbert, D. Alamargot, and M.-F. Morin, "Handwriting on a tablet screen: role of visual and proprioceptive feedback in the control of movement by children and adults," *Human movement science*, vol. 65, pp. 30–41, 2019.

[27] G. Srimathveeravalli and K. Thenkurussi, "Motor skill training assistance using haptic attributes," in *First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics Conference*. IEEE, 2005, pp. 452–457.

[28] K. Henmi and T. Yoshikawa, "Virtual lesson and its application to virtual calligraphy system," in *Proceedings. 1998 IEEE International Conference on Robotics and Automation (Cat. No.98CH36146)*, vol. 2, May 1998, pp. 1275–1280 vol.2.

[29] B. Bayart, A. Pocheville, and A. Kheddar, "An adaptive haptic guidance software module for i-touch: example through a handwriting teaching simulation and a 3d maze," in *IEEE International Workshop on Haptic Audio Visual Environments and their Applications*, Oct 2005, pp. 6 pp.–.

[30] M. Xiong, I. Milleville-Pennel, C. Dumas, and R. Palluel-Germain, "Comparing haptic and visual training method of learning chinese handwriting with a haptic guidance," *JCP*, vol. 8, pp. 1815–1820, 2013.

[31] N. Pedemonte, T. Laliberté, and C. Gosselin, "A bidirectional haptic device for the training and assessment of handwriting capabilities," in *2013 World Haptics Conference (WHC)*, April 2013, pp. 599–604.

[32] M. M. Boroujeni and A. Meghdari, "Haptic device application in persian calligraphy," in *2009 International Conference on Computer and Automation Engineering*, March 2009, pp. 160–164.

[33] M. M. Amin, H. B. Zaman, and A. Ahmad, "Visual haptic approach complements learning process of jawi handwriting skills," in *2013 5th International Conference on Information and Communication Technology for the Muslim World (ICT4M)*. IEEE, 2013, pp. 1–6.

[34] A. Teranishi, G. Korres, W. Park, and M. Eid, "Combining full and partial haptic guidance improves handwriting skills development," *IEEE transactions on haptics*, vol. 11, no. 4, pp. 509–517, 2018.

[35] W. Park, G. Korres, T. Moonesinghe, and M. Eid, "Investigating haptic guidance methods for teaching children handwriting skills," *IEEE transactions on haptics*, 2019.

[36] N. Pernalete, S. Edwards, R. Gottipati, J. Tipple, V. Kolipakam, and R. V. Dubey, "Eye-hand coordination assessment/therapy using a robotic haptic device," in *9th International Conference on Rehabilitation Robotics, 2005. ICORR 2005.*, June 2005, pp. 25–28.

[37] N. Subrahmaniyan, S. Krishnaswamy, A. Chowriappa, G. Srimathveeravalli, A. Bisantz, L. Shriber, and T. Kesavadas, "A visual haptic system for children with learning disabilities: Software and hardware design considerations," *Journal of Interactive Learning Research*, vol. 23, pp. 113–141, 04 2012.

[38] J. Mullins, C. Mawson, and S. Nahavandi, "Haptic handwriting aid for training and rehabilitation," in *2005 IEEE International Conference on Systems, Man and Cybernetics*, vol. 3, Oct 2005, pp. 2690–2694 Vol. 3.

[39] Y. Kim, Z. Duric, N. L. Gerber, A. R. Palsbo, and S. E. Palsbo, "Poster: Teaching letter writing using a programmable haptic device interface for children with handwriting difficulties," in *2009 IEEE Symposium on 3D User Interfaces*, March 2009, pp. 145–146.

[40] Y. Kim, M. Collins, W. Bulmer, S. Sharma, and J. Mayrose, "Haptics assisted training (hat) system for children's handwriting," in *2013 World Haptics Conference (WHC)*, April 2013, pp. 559–564.

[41] W. Park, G. Korres, S. Tahir, and M. Eid, "Evaluation of handwriting skills in children with learning difficulties," in *Universal Access in Human-Computer Interaction. Multimodality and Assistive Environments*, M. Antona and C. Stephanidis, Eds. Cham: Springer International Publishing, 2019, pp. 150–159.

[42] S. Martin and N. Hillier, "Characterisation of the novint falcon haptic device for application as a robot manipulator," in *Australasian Conference on Robotics and Automation (ACRA)*, December 2009, pp. 291–292.

[43] D. Wechsler, "The Wechsler intelligence scale for children (5th ed.)." Bloomington: The Psychological Corporation, 2014.

[44] B. Lewis, "WISC - V," in *Encyclopedia of Autism Spectrum Disorders*, F. R. Volkmar, Ed. New York, NY: Springer New York, 2017, pp. 1–6.

[45] D. Wechsler, "WPPSI-III technical and interpretive manual." San Antonio, Tex: The Psychological Corporation, 2002.

[46] "WPPSI-III," in *Encyclopedia of Autism Spectrum Disorders*, F. R. Volkmar, Ed. New York, NY: Springer New York, 2013, pp. 3400–3400.

[47] T. Asselborn, T. Gargot, . Kidziński, W. Johal, D. Cohen, C. Jolly, and P. Dillenbourg, "Automated human-level diagnosis of dysgraphia using a consumer tablet," *NPJ digital medicine*, vol. 1, no. 1, pp. 1–9, 2018.

[48] A. Overvelde and W. Hulstijn, "Handwriting development in grade 2 and grade 3 primary school children with normal, at risk, or dysgraphic characteristics," *Research in developmental disabilities*, vol. 32, no. 2, pp. 540–548, 2011.

[49] P. Diakakis, J. Gardelis, K. Ventouri, K. Nikolaou, G. Koltsida, S. Tsitoura, and A. Constantopoulos, "Behavioral problems in children with learning difficulties according to their parents and teachers," *Pediatrics*, vol. 121, no. Supplement 2, pp. S100–S101, 2008.

[50] R. Sigrist, G. Rauter, R. Riener, and P. Wolf, "Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review," *Psychonomic bulletin & review*, vol. 20, no. 1, pp. 21–53, 2013.

[51] R. Sigrist, G. Rauter, R. Riener, and P. Wolf, "Terminal feedback outperforms concurrent visual, auditory, and haptic feedback in learning a complex rowing-type task," *Journal of motor behavior*, vol. 45, no. 6, pp. 455–472, 09 2013.

[52] R. Sigrist, G. Rauter, L. Marchal-Crespo, R. Riener, and P. Wolf, "Sonification and haptic feedback in addition to visual feedback enhances complex motor task learning," *Experimental brain research*, vol. 233, no. 3, pp. 909–925, 2015.

[53] A. H. Waterman, J. Havelka, P. R. Culmer, L. J. Hill, and M. Mon-Williams, "The ontogeny of visual–motor memory and its importance in handwriting and reading: a developing construct," *Proceedings of the Royal Society B: Biological Sciences*, vol. 282, no. 1798, p. 20140896, 2015.

[54] M. A. Guadagnoli and T. D. Lee, "Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning," *Journal of motor behavior*, vol. 36, no. 2, pp. 212–224, 2004.

[55] B. Z. Mahon, "What is embodied about cognition?" *Language, cognition and neuroscience*, vol. 30, no. 4, pp. 420–429, 2015.

[56] K. H. James and T. P. Atwood, "The role of sensorimotor learning in the perception of letter-like forms: Tracking the causes of neural specialization for letters," *Cognitive Neuropsychology*, vol. 26, no. 1, pp. 91–110, 2009.

[57] F. Bara and N. Bonneton-Botté, "Learning letters with the whole body: Visuomotor versus visual teaching in kindergarten," *Perceptual and motor skills*, vol. 125, no. 1, pp. 190–207, 2018.

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Appendix

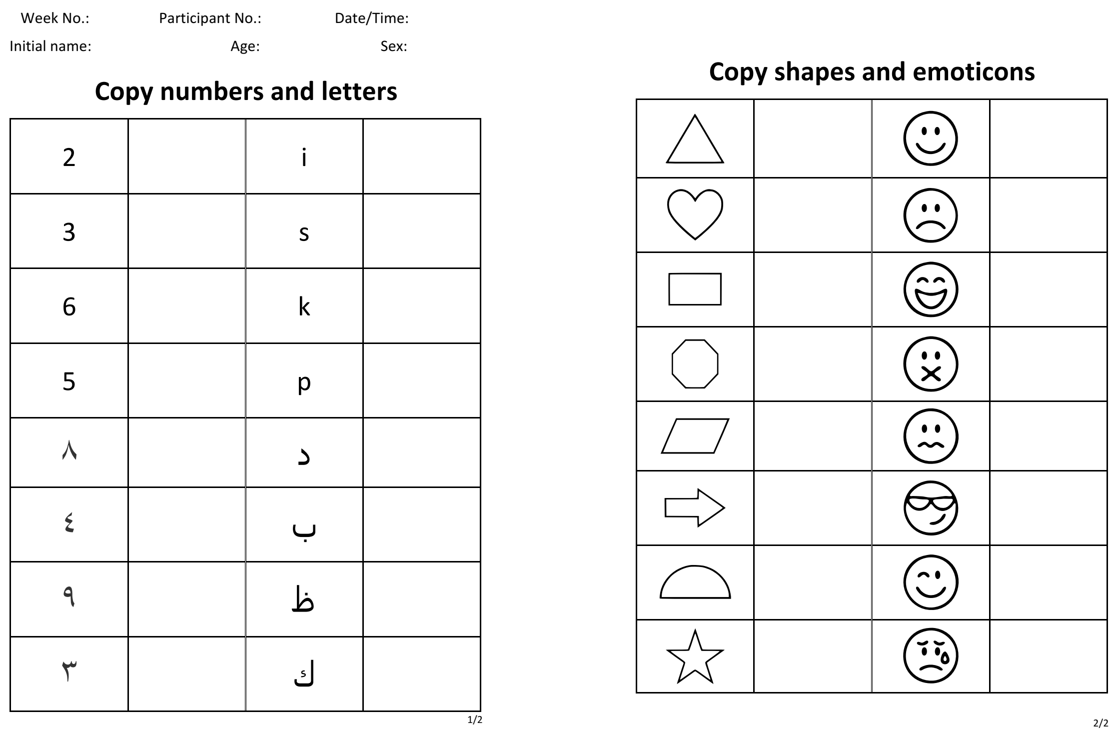

Fig. 3: sheets of the paper-based copy work.