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Effects of Full/Partial Haptic Guidance on Handwriting Skills Development

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***Abstract*— It has been shown in previous studies that haptic guidance improves the learning outcomes of handwriting motor skills. In this paper, we present a comparison between full guidance and partial guidance using a haptic learning tool which supports these two modes. The full guidance mode leads the user along a pre-recorded trajectory, whereas the partial guidance mode allows the user a free movement and provides corrective forces if they deviate significantly from the desired path. Experimental results with 22 participants demonstrated that there is no significant difference between partial haptic guidance and full haptic guidance for improving learning outcomes, while both have significantly improved the learner's performance compared to no haptics feedback. However, when the two modes are combined, partial guidance followed by full guidance yielded better overall performance. We conclude the paper by summarizing our findings and providing perspectives for future work.**

I. INTRODUCTION

The development of handwriting skills is a fairly complex sensorimotor task that is best learned through practice and refinement. Millions of children around the world attend school to learn how to write using their visual modality. While it is true that continuous visual feedback is an essential part of the learning process, previous studies have shown that incorporating the haptic modality in training handwriting can increase the learning ability [1]. Haptic technologies allow for seamless and efficient incorporation of the sense of touch for handwriting acquisition. Haptics refers to the emerging discipline that studies the communication of haptic sensations between the human and the digital world [2].

Studies have also revealed a correlation between handwriting of single letters and reading acquisition as well as spelling skills [3]. Therefore, handwriting plays an important role when learning linguistics. This is where haptic technology can be used for linguistic skills development.

Building on previous studies that demonstrate the effectiveness of haptic technologies on practicing handwriting, this paper presents a study that aims to compare and contrast the effectiveness of haptic learning with partial haptic guidance versus full haptic guidance. It utilizes an existing multimedia system that combines visual, auditory and haptic feedback to enrich the learning ability of the students' handwriting of (Arabic) alphabetical characters. The full guidance mode leads the user along a prescribed trajectory, whereas the partial guidance allows the user to freely follow along the trajectory while still controlling for extreme deviations from the prescribed path. Results of the study will allow educators to make decisions on whether to use partial or full haptic guidance based on concrete evidence obtained by conducting user experiments.

The remainder of the paper is organized as follows. Section II analyzes the related work for haptic-based handwriting. In section III, both software and hardware components of the haptic learning tool are described. Section IV presents the experimental setup, procedure, and a discussion of the findings. Finally, section V summarizes the study findings and provides perspectives for future work.

II. RELATED WORK

There have been various studies on the effect of haptic guidance on training a motor skill. In [4], the subjects were trained to learn and recreate a complex 3-D trajectory. Results showed that the haptic plus visual training method outperformed significantly the visual-only and haptics-only methods. The I-TOUCH haptic guidance software, described in [5], supported three haptic guidance modes: (1) full guidance, (2) partial guidance, and (3) simple correction – similar to partial guidance, but the user was pulled back to the path without taking into account the trajectory's direction. Results showed that the haptic assistance was useful, but no significant difference was noticeable between the full guidance method and the partial guidance method. Their study lacked a formal evaluation of the different modes concerning their assistance performance in handwriting learning, which is what we are trying to evaluate in this paper (note that our haptic partial guidance is more similar to the simple correction mode than the partial mode).

A subsequent work investigated the impact of haptic steering guidance on curve negotiation behavior [6]. It was concluded that the curve negotiation performance was improved with haptic guidance. Additionally, when the haptic guidance was used, the control activity increased, showing a growing struggle between the driver's and the guidance system's steering actions. Another study demonstrated that haptic guidance caused interference in motor learning which led to a lower motor skills training efficacy [7]. Similar studies investigated the performance of haptic disturbance and concluded that combining haptic guidance and disturbance could improve motor learning [8][9].

Several studies investigated the effectiveness of haptic feedback for teaching handwriting in different languages. Haptic-based simulation is applied for Japanese characters

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[5][10][11], Chinese characters [12], Latin letters [13][14], and Persian calligraphy [15]. For instance, systems that utilizes haptic modality to teach handwritten characters were presented in [10] and [16]. The systems implemented a function to record the instructor's hand motions and play back the recordings to a student who can feel the instructor's style of handwriting using a haptic device. Other studies have investigated the use of haptics for teaching handwriting to typical children [13] and to children with learning difficulties [17][18][19], all focusing on full haptic guidance.

Beyond the technical constraints related to its complex implementation, the two main drawbacks for haptic-based handwriting are: firstly, full haptic guidance causes a passive learning experience. Secondly, the required tools are currently costly, a fact that renders home-based, personal training unaffordable for most learners. Therefore, the goal of this study is to propose an affordable haptic-based learning system and to investigate how partial and/or full haptic guidance are utilized to maximize the learning outcomes. In this study, following hypotheses were examined:

(i) The mode of haptic guidance (partial or full) is significant for improving the learning outcomes. This is to test if one haptic guidance mode results in better learning outcomes than the other.

(ii) In case the two modes of haptic guidance are to be combined, the order at which these modes are used is significant (starting with full haptic guidance followed by partial haptic guidance or vice versa).

(iii) The improvement in performance between the end of the first session and the end of the last session is significant for both full and partial guidance.

III. HAPTIC HANDWRITING SYSTEM

A. Haptic Handwriting System Architecture

A haptic handwriting system is developed to investigate the effects of full/partial haptic guidance on the learning outcomes for Arabic handwriting. A simplified architecture of the proposed system is shown in Fig. 1. It comprises six modules: 1) a language repository (storing Arabic characters data); 2) haptic rendering; 3) audio and visual rendering; 4) haptic interface; 5) a Quality of Performance Evaluation module; and 6) a Graphical User Interface (GUI). Note that the haptic system setup is cost effective (less than $300 US, $250 for the Novint Falcon device and less than $50 for the custom grip and software). The architecture modules are described in more details herein:

- *Language Repository.* This repository contains the study material presented to the learner, including the alphabet's symbol images, the pronunciation files (auditory), and the haptic stimuli (position trajectory to create the movements necessary to draw a character). The haptic data was recorded by a native Arabic calligraphy expert.
- *The Haptic Rendering.* The haptic rendering module reads the haptic data (a series of timestamped positions) and then computes and applies the appropriate forces to move the haptic interface along the desirable trajectory. Two haptic rendering modes are supported: full haptic guidance and partial haptic guidance. In the full guidance mode, the user is passively led by the haptic device; while in the partial guidance mode, the haptic device provides supportive forces to return the learner's hand to the correct path, only when there is a significant trajectory deviation.
- *The Audio-Visual Rendering.* When the learner selects a particular handwriting task, the application will do the following: 1) invoke the graphic rendering to sketch the handwriting task; 2) display images in a review area; 3) load the corresponding audio file(s); and 4) load the haptic stimulus for haptic playback.
- *The Haptic Interface.* A haptic device that can be used in two ways. At the beginning, an expert can interact with it to record new alphabet characters; and afterwards, a student can use it to learn how to write these characters with the device's assistance.
- *Quality of Performance Evaluation.* A component to evaluate the student's learning performance. This is analyzed in more detail in section IV-B.
- *The Graphical User Interface.* The GUI is made up of two windows: instructor window and the student window. The student window (Fig. 2) enables the learner to load and play back handwriting tasks. The instructor window enables the instructor to author handwriting tasks by recording haptic, audio, visual contents and assign these tasks to a learner.

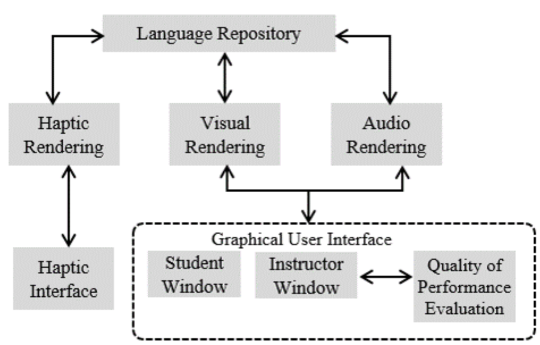

Fig. 1. Proposed architecture of the haptic handwriting system.

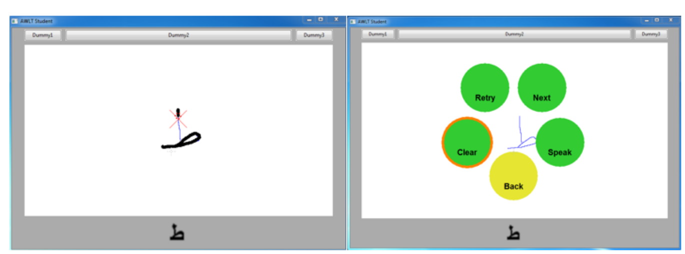

Fig. 2. Student window. Drawing area with the recorded letter (left) and the user menu (right).

B. Haptic Interface and Rendering

A custom grip for the Novint Falcon device was designed using the SolidWorks 3-D CAD software and printed using a 3-D printer. The grasp is a pen-like stylus, with maximized workspace and flexible orientation, so learners can rotate it depending on their left/right handedness. The overall design (the Falcon haptic device and the pen-like stylus) is assembled as shown in Fig. 3.

The haptic recording and playback functionalities are also implemented to conduct the experiment. In this study, two haptic guidance algorithms are developed: full haptic guidance and partial haptic guidance. We give below a high-level description of these algorithms:

- *Full Haptic Guidance Algorithm.* The full haptic guidance algorithm is used to reconstruct the trajectory created by the instructor for handwriting in Arabic. The recorded data includes a time-stamped series of position data that defines the stroke sequence for the handwriting. The user is passively led by the device to reconstruct the character. The full haptic guidance algorithm is based on the method used in [4].
- *Partial Haptic Guidance Algorithm.* In the partial haptic guidance scenario, the error between the trajectory constructed by the learner and the desired trajectory for the respective handwriting is used to render a "corrective" force that brings the learner's hand back to the desired trajectory. The algorithm is based on generating an active force towards the desired trajectory. The pseudocode for the partial haptic guidance algorithm is shown below. The algorithm assumes co-centered inner and outer force fields with radii `in_dist` and `out_dist` respectively. Whenever the haptic device is within the outer ring, larger forces are applied than when the device is in the inner ring. If the distance is tolerance or smaller, then no forces are applied. Finally, the calculated force is normalized so the haptic playback does not cause any abrupt changes in the generated forces.

Listing 1. Partial Guidance Algorithm Pseudocode

```
out_dist  # outer threshold
in_dist   # inner threshold
distance  # distance between HIP position and path
ref_force # reference force
tolerance # min distance error for feedback

if (distance < out_dist)
  if (distance > in_dist)           # in outer ring
    force=(out_dist-distance)/(out_dist-in_dist)*ref_force
  else if (distance >= tolerance)   # in inner ring
    force=(distance-in_dist)/(in_dist-tolerance)*ref_force
  else
    force = 0
  if (force > ref_force)
    force = ref_force
  normalizeSafe (force)
return (force)
```

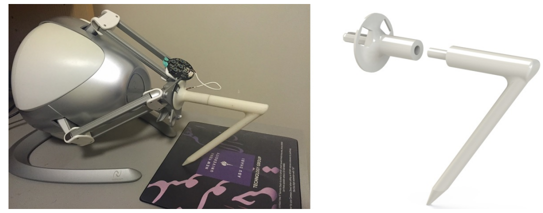

Fig. 3. Haptic learning tool (left) and its pen-like stylus (right).

IV. Experiment Design and Analysis

A. Experimental Setup

The experimental setup included a laptop, the haptic interface (Novint Falcon haptic device with the custom grip), and the software application running on the laptop. The laptop has an Intel Core i7-2640M CPU running at 2.80 GHz, 8 GB of RAM, an Intel HD Graphics 3000, and runs Windows 7 professional operating system (64-bit). The Novint Falcon is a low-cost 3-DOF haptic device designed originally for the gaming industry [20]. The Falcon device is characterized by a 10x10x10 cm workspace and 8.9 N of maximum producible force. A snapshot of the experimental setup is shown in Fig. 4.

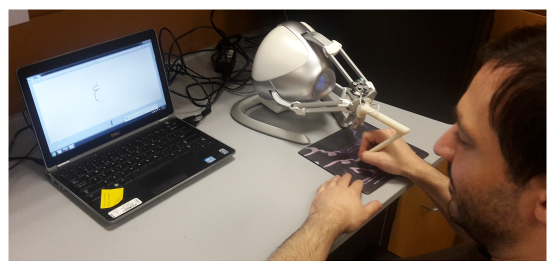

Fig. 4. Experimental setup.

B. Procedure and Evaluation Metrics

Participants who had no previous experience with reading or writing Arabic were selected for this experiment in order to assess the effectiveness of the learning tool with partial and full haptic guidance. A total number of 22 adult users participated in the experiment who were divided into two groups, each one consisting of 5 females and 6 males. The age range was 18 to 45 years.

In order to eliminate the effects from unfamiliarity with the experiment setup, the participants were allowed to practice on a few English letters to accustom themselves with the software and hardware before conducting the experiment.

The two different groups trained, for six training sessions, with the same three Arabic characters, shown in Fig. 5, which were selected from different families of Arabic letters. The reference Arabic alphabet was recorded by a hired Arabic calligraphy handwriting expert who was also assigned the task of the subjective evaluation of the participants' performance at the end of the experiment. Group 1 began its training with the full haptic guidance mode in the first three sessions and then moved on using the partial haptic guidance in the last three sessions. Group 2, on the other hand, started with the partial (first three sessions) and continued with the full haptic guidance mode (three last sessions). The first three sessions were trained on the first day, and the last three sessions were trained on the second day. Between the sessions there was always at least a 30-minutes break in order to minimize the effects of haptic fatigue [21]. In every session, the participants were asked to practice the selected three Arabic characters, 15 times each, with the help of either the full or partial haptic guidance. At the end of each session, they were instructed by the experimenter to write these three letters using the haptic device in free writing mode, i.e. they could draw freely on the surface without any assistance from the full/partial guidance modes. Once all the sessions were conducted, the participants were instructed to answer a questionnaire for: 1) describing each haptic modes, 2) evaluating the overall experience such as usefulness and joy (7 Likert-scale), and 3) measuring the effectiveness of the two haptic modes (7 Likert-scale).

Fig. 5. The selected Arabic letters: Haa (left), Kaaf (middle), Taa (right).

To evaluate the fidelity of the letters written by the subjects, we followed a two-pronged approach involving subjective and algorithmic evaluations. For the subjective evaluation, the Arabic handwriting expert was asked to evaluate the performance of the participants on a scale of 0 to 10 (if the shape of the letter written by a subject was identical to the shape of the expert's letter, then this subject would get a score of 10), and the scores were converted into a scale of 0 to 100. For the algorithmic evaluation, we first saved all the letters as images and then we considered a number of image similarity measures which we describe in detail next.

Image similarity metrics basically match points based on local similarity between images. There are two general approaches, namely, correlation-based approaches and feature-based approaches [22]. Correlation-based approaches match image patches using correlation and assume only a translational difference between the two local patches (no rotation, or differences in appearance due to perspective). This approach works well for scenes with lots of texture but is inadequate for sparse scenes. Feature-based approaches, on the other hand, match edges, lines, or corners and may be better for scenes with little texture. For this particular hand-writing evaluation application, a combined approach was utilized. A feature-based method, that is invariant to scale, rotation, and translation, was applied first to account for the fact that the letters could be of different sizes and skewed. Then, the correlation between the two images was calculated.

The Scale Invariant Feature Transform (SIFT) [23] transforms an image into a set of features that are invariant to scale. These features are then used to match points in an image. Fig. 6 shows an implementation of this algorithm in Matlab. The figure shows the expert's handwriting on the left side and the participant's on the right.

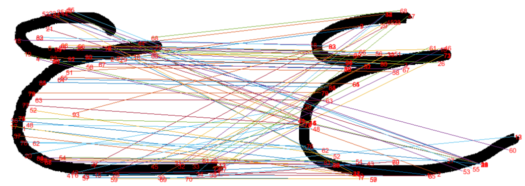

Fig. 6. SIFT point matching.

It is immediately obvious from Fig. 6, however, that the SIFT algorithm returns some false positive matches. We, therefore, need an outlier detection algorithm to clean up these matches. RANSAC (RANdom SAmple Consensus) [24] is one such algorithm. Given a set of 2D data points, RANSAC finds the transformation which minimizes the sum of squared perpendicular distances (orthogonal regression), subject to the condition that none of the valid points deviates from this transformation by more than t units. After applying RANSAC, the matches appear with no false positives in Fig. 7, as desired. Finally, the correlation between the images is calculated as a score in the 0-100 range too.

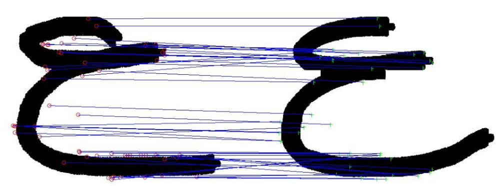

Fig. 7. RANSAC outlier detection.

C. Results and Analysis

To test the first hypothesis, we compare the average scores of the first three sessions for both partial and full guidance between Group 1 and Group 2 as shown in Fig. 8 (algorithmic evaluation) and Fig. 9 (expert evaluation). The difference in the average score is less than 1%. Therefore, the first hypothesis is rejected and thus there is no significant difference between full and partial guidance as far as the learning outcomes are concerned.

An interesting observation, though, is that the partial haptic guidance resulted in better participants' experience compared to the full haptic guidance (Fig. 11). A possible explanation of this result is two-fold: interactivity and realism. Participants felt passive when using the full haptic guidance and thus their engagement in the task was lower. Moreover, the partial guidance experience seemed to imitate the test procedure's free writing mode better than the full guidance experience, and therefore partial was more realistic to use and yielded better scores.

The second hypothesis is related to combining both partial and full haptic guidance modes by examining the differences in performance between Group 1 and Group 2 (Group 1 started with three sessions of full guidance followed by three sessions of partial; Group 2's guidance sequence was vice versa). We compare the average scores the participants earned by the end of the first session and the end of the last session for both expert and algorithmic evaluations. This is depicted in Fig. 10. The improvement in the average score for Group 2 (21.5%) is significantly higher than the improvement in the average score for Group 1 (16.1%). The same conclusion can be derived by examining Fig. 8 (algorithmic evaluation) and Fig. 9 (expert evaluation). The average score of each group, along with the standard errors, for the two distinct haptic guidance modes across the six training sessions is calculated (first three with one guidance mode and last three with the other guidance mode). To examine the improvement differences between guidance modes, a paired t-test was conducted for each group. As a result, in the algorithmic evaluation case, the improvement is not statistically significant in Group 1 ($t(10)=1.61$, n.s.), but it is significant in Group 2 ($t(10)=5.55$, $p<0.05$). In the expert evaluation, the improvement is significant in both Group 1 ($t(10)=2.36$, $p<0.05$) and Group 2 ($t(10)=3.71$, $p<0.05$). This demonstrates that the order, in which the modes are used, is significant, thus the second hypothesis is considered to be true. In particular, Group 2, which started with the partial guidance mode, has performed better than Group 1, which started with the full guidance.

Finally, in order to examine the third hypothesis, we examine Fig. 10. The improvement in the average score for both groups is significant (16.1% for Group 1 and 21.5% for Group 2). This indicates that haptic guidance in general is useful for teaching handwriting skills whether in full or partial guidance modes. The third hypothesis is valid.

Note that the algorithmic evaluation is about 20% lower than the expert's evaluation. The primary reason for this is that humans basically apply a true or false mechanism and therefore tend to give a higher grade, as long as they are able to distinguish the letters [25]. The algorithm makes no allowances for such approximations. Nevertheless, the trends of both evaluations are similar.

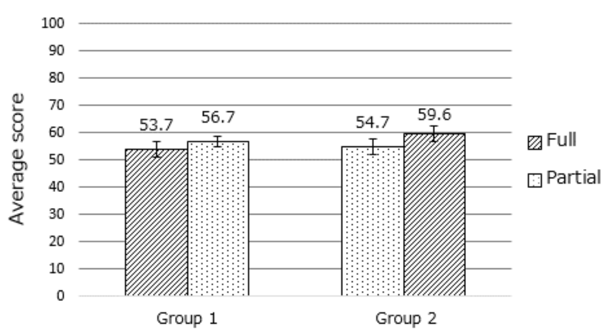

Fig. 8. Algorithmic evaluation of the subjects' handwriting. Mean score values and standard errors for the first and second guidance mode used per group.

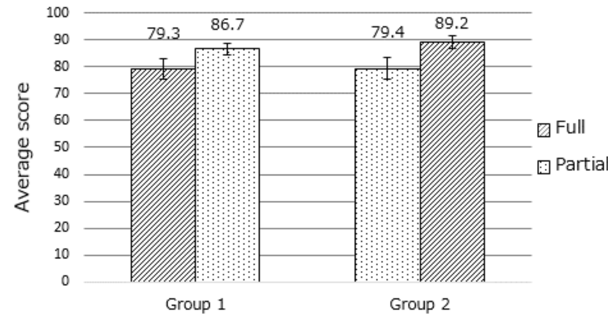

Fig. 9. Subjective-expert evaluation of the subjects' handwriting. Mean score values and standard errors for the first and second guidance mode used per group.

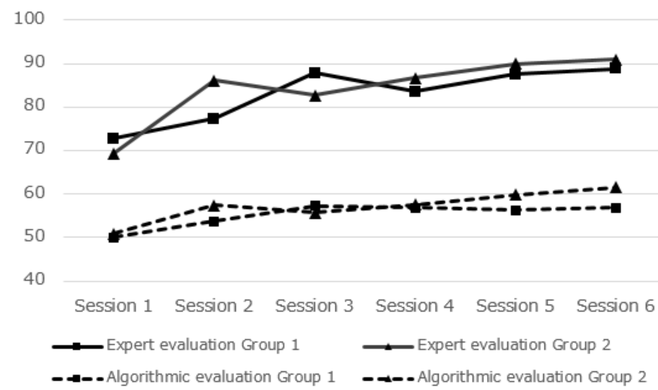

Fig. 10. Expert (top) and algorithmic (bottom) evaluations.

D. Results from the Questionnaire

After the completion of the experiment, the completed questionnaires are analyzed. Based on the participants' responses, the following conclusions came forth:

1) The subjects were asked to describe how the partial and the full guidance modes work. 90.91% of the participants described correctly the two haptic modes, so these two modes are considered perceptually different.
2) The participants also answered if they thought that the haptic learning tool was: i. a useful device to learn a language alphabet, and ii. an enjoyable and pleasant apparatus to work with. It was regarded as useful by the 95.45% of the participants (with an average score of 5.64 out of 7); and by the same percentage, 95.45%, as enjoyable and pleasant (with an average score of 5.91 out of 7). By defining "User Satisfaction" as the average of usefulness and enjoyability, it is derived that 95.45% of the participants were satisfied (with an average score of 5.78 out of 7) by the haptic learning tool.
3) Another useful analysis is comparing the two subjective evaluations: the expert against the participant's experience which transpired in the questionnaire. The experiment participants were asked to evaluate the effectiveness (how well they thought they learned to write the letters) of each guidance mode. This graph is shown in Fig. 11.

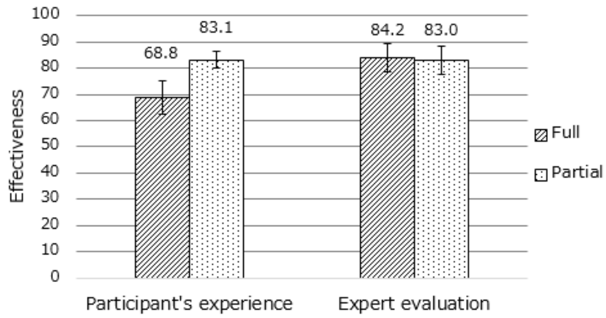

Fig. 11. Participant's and expert evaluations for the partial / full modes. Mean score values and standard errors for the two guidance modes.

We can see that the expert's evaluation is high for both modes. But the users' evaluation for the partial is higher than the full mode, indicating a user preference to partial mode, probably because it's not as restrictive as the full.

4) At the end of the questionnaire, there was a space for comments on how to improve the haptic learning tool. The most common observation was to make the 3-D printed pen-like stylus more ergonomic to use.
5) Comparing partial haptic guidance and full haptic guidance, it seems that when learning the gross aspects about handwriting trajectory, partial guidance is more efficient, while learning fine details of the handwriting is conveyed better with full guidance. This suggests that learning generic handwriting skills may utilize partial haptic guidance, whereas personalized handwriting skills can be learned better through full guidance.

V. CONCLUSIONS

In this paper, a study is presented to evaluate the effects of partial/full haptic guidance on the learning outcomes for learning Arabic characters handwriting. Results show that (1) there is no significant difference between partial and full haptic guidance to improve learning outcomes, (2) partial guidance followed by full guidance is considered to yield better performance, and (3) both partial and full haptic guidance yielded significant improvement in handwriting acquisition. The conclusions derived from this study may guide the development of haptic guidance (partial and/or full) in various applications related to education and training. Our immediate future work includes conducting an experimental study with typical children as well as children with learning difficulties. Another consideration could be to improve the ergonomics of the haptic tool's stylus.

REFERENCES

[1] M. Mansour, M. Eid, and A. Saddik, "A multimedia handwriting learning and evaluation tool," *Proc. Intelligent Interactive Learning Object Repositories (I2LOR)*, 2007.
[2] M. Eid, M. Orozco, and A. El Saddik, "A guided tour in haptic audio visual environments and applications," *Int. J. of Advanced Media and Communication*, vol. 1, no. 3, pp. 265–297, 2007.
[3] P. Gimenez, N. Bugescu, J. M. Black, R. Hancock, K. Pugh, M. Nagamine, E. Kutner, P. Mazaika, R. Hendren, B. D. McCandliss *et al.*, "Neuroimaging correlates of handwriting quality as children learn to read and write," *Frontiers in human neuroscience*, vol. 8, 2014.
[4] D. Feygin, M. Keehner, and R. Tendick, "Haptic guidance: Experimental evaluation of a haptic training method for a perceptual motor skill," in *10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE, 2002, pp. 40–47.
[5] 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 Int. workshop on haptic audio visual environments and their applications*, 2005, pp. 6–pp.
[6] M. Mulder, D. A. Abbink, and E. R. Boer, "The effect of haptic guidance on curve negotiation behavior of young, experienced drivers," in *IEEE Int. Conf. on Systems, Man and Cybernetics*. IEEE, 2008, pp. 804–809.
[7] Y. Li, V. Patoglu, and M. K. O'Malley, "Negative efficacy of fixed gain error reducing shared control for training in virtual environments," *ACM Trans. on Applied Perception (TAP)*, vol. 6, no. 1, p. 3, 2009.
[8] J. Lee and S. Choi, "Effects of haptic guidance and disturbance on motor learning: Potential advantage of haptic disturbance," in *IEEE Haptics Symposium*. IEEE, 2010, pp. 335–342.
[9] H. Lee and S. Choi, "Combining haptic guidance and haptic disturbance: an initial study of hybrid haptic assistance for virtual steering task," in *IEEE Haptics Symposium*. IEEE, 2014, pp. 159–165.
[10] K. Henmi and T. Yoshikawa, "Virtual lesson and its application to virtual calligraphy system," in *IEEE International Conference on Robotics and Automation*, vol. 2. IEEE, 1998, pp. 1275–1280.
[11] H. Nishino, K. Murayama, T. Kagawa, and K. Utsumiya, "A japanese calligraphy trainer based on skill acquisition through haptization," in *24th IEEE Int. Conf. on Advanced Information Networking and Applications*. IEEE, 2010, pp. 1225–1232.
[12] F. Ecole des Mines de Nantes *et al.*, "Comparing haptic and visual training method of learning chinese handwriting with a haptic guidance," 2013.
[13] 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 Conf. and Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE, 2007, pp. 72–77.
[14] N. Pedemonte, T. Laliberté, and C. Gosselin, "A bidirectional haptic device for the training and assessment of handwriting capabilities," in *World Haptics Conference*. IEEE, 2013, pp. 599–604.
[15] M. M. Boroujeni and A. Meghdari, "Haptic device application in persian calligraphy," in *Int. Conf. on Computer and Automation Engineering*. IEEE, 2009, pp. 160–164.
[16] K. Shuto, H. Nishino, T. Kagawa, and K. Utsumiya, "A handwritten character training system with haptization of instructor's brush-strokes," in *Int. Conf. on Complex, Intelligent and Software Intensive Systems*. IEEE, 2009, pp. 1030–1035.
[17] J. Mullins, C. Mawson, and S. Nahavandi, "Haptic handwriting aid for training and rehabilitation," in *IEEE Int. Conf. on Systems, Man and Cybernetics*, vol. 3. IEEE, 2005, pp. 2690–2694.
[18] Y.-S. Kim, M. Collins, W. Bulmer, S. Sharma, and J. Mayrose, "Haptics assisted training (hat) system for children's handwriting," in *World Haptics Conference*. IEEE, 2013, pp. 559–564.
[19] 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 *IEEE Symposium on 3D User Interfaces*. IEEE, 2009, pp. 145–146.
[20] S. Martin and N. Hillier, "Characterisation of the novint falcon haptic device for application as a robot manipulator," in *Australasian Conf. on Robotics and Automation (ACRA)*. Citeseer, 2009, pp. 291–292.
[21] A. Hamam and A. El Saddik, "User force profile of repetitive haptic tasks inducing fatigue," in *Seventh International Workshop on Quality of Multimedia Experience*. IEEE, 2015, pp. 1–6.
[22] J. L. Mundy and A. Zisserman, "Appendix-projective geometry for machine vision," 1992.
[23] D. G. Lowe, "Distinctive image features from scale-invariant keypoints," *Int. J. of computer vision*, vol. 60, no. 2, pp. 91–110, 2004.
[24] M. A. Fischler and R. C. Bolles, "Random sample consensus: a paradigm for model fitting with applications to image analysis and automated cartography," *Communications of the ACM*, vol. 24, no. 6, pp. 381–395, 1981.
[25] L. A. Zadeh, "Fuzzy sets," *Information and control*, vol. 8, no. 3, pp. 338–353, 1965.