Combining Full and Partial Haptic Guidance Improves 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. Full and partial haptic guidance are developed and evaluated in the literature. In this paper, we present two experimental studies to examine whether combining full and partial haptic guidance is more effective for improving handwriting skills than merely full or partial guidance methods. Experiment I, with 22 participants, compares the effectiveness of merely full and partial haptic guidance methods towards improving learning outcomes of Arabic handwriting. Even though haptic guidance in general is found to be effective and pleasant by all participants, experiment I concludes that there are no statistically significant differences in the learning outcomes between full and partial haptic guidance. Experiment II investigates whether a combination of full and partial haptic guidance could further improve the learning outcomes, compared to merely full or partial haptic guidance. The learning outcomes and quality of experience are measured to evaluate each group's performance. Results from experiment II demonstrate that the combination of full and partial haptic guidance results in statistically significant improvements in the quality of handwriting, compared to mere full or partial haptic guidance. In particular, starting with partial haptic guidance at early stage of learning and then using full guidance at intermediate/advanced learning stages seemed to be the most effective. This implies that partial haptic guidance is more effective to learn the gross shape of handwriting skills (at early stages of the learning process) whereas full haptic guidance is more effective to learn the fine details of the handwriting skills (at intermediate or advanced stage of learning). Therefore, partial-then-full haptic guidance seems to be the most effective to improve learning outcomes.

Index Terms—Haptic interfaces, evaluation/methodology, psychology, user-centered design

1 Introduction

Handwriting is a fairly complex sensorimotor task that requires perceptual, motor, cognitive and linguistic skills, and is best learned through practice and refinement [1]. Today, most of our handwriting learning tools are based on audio-visual modalities. Handwriting teaching involves showing learners how to produce relatively complex shapes according to a standard. In order to produce the letter trajectory, learners must develop perceptual, motor and visual-motor integration skills. The human sense of touch, or haptics, plays a prominent role in developing motor and visual-motor integration skills [2].

Haptics refers to the emerging discipline that studies the design of hardware and software systems to communicate touch sensations (both tactile and kinesthetic) between the human and a remote or virtual environment [2]. Haptic technologies strive for intuitive and efficient incorporation of the sense of touch into different applications, including handwriting acquisition. Several studies have demonstrated that incorporating the haptic modality into handwriting skills development can increase the learning effects [3]. Existing studies have also revealed a significant correlation between handwriting of single letters and reading/spelling skills [4]. Therefore, handwriting skills development plays an important role when learning linguistics.

Haptic guidance methods are developed to support the learning of handwriting skills by physically moving the learner's hand along the desired trajectory. There exist several types of haptic guidance, including full guidance or partial guidance [3]. In full haptic guidance, the haptic interface leads the handwriting task while the learner is passively following the movements. Partial haptic guidance allows the user to construct the handwriting task but when significant errors are detected between the generated handwriting and the reference handwriting, the device provides corrective force feedback to put the learner back on the reference trajectory. To the best of our knowledge, there exists no formal study to investigate the effectiveness of combining partial and full haptic guidance methods towards improving learning outcomes for handwriting skills development.

In our previous work [5], a study is presented to investigate how combining full and partial haptic guidance affects the learning outcomes of handwriting skills. Building on the previous study, this paper aims to compare and contrast the effectiveness of haptic guidance methods, namely full guidance, partial guidance and the combination of full-partial (combining full and partial haptic guidance at different stages of the learning process) towards improving learning outcomes and overall quality of user experience. Since the effect of haptic guidance has already been shown in literature [6], [7], we did not consider a control group that do training without any haptic guidance.

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The study utilizes an existing multimedia system that combines visual, auditory and haptic feedback to enrich the handwriting of Arabic letters. Results of the study will allow educators to make decisions regarding haptic guidance based on quantitative evidence obtained by conducting user experiments.

The remainder of the paper is organized as follows. Section 2 analyzes the related work for haptic-based handwriting. Section 3 presents experiment I that involves comparing full and partial haptic guidance. Section 4 describes experiment II, which compares the combination of full and partial haptic guidance methods towards improving learning outcomes. Section 5 presents a discussion about the subjective and end-effector analysis derived from both experiments. Finally, Section 6 summarizes the findings of the study and provides perspectives for future work.

2 Related Work

2.1 Haptic Guidance for Motor Skills Development

Early studies on the effect of haptic guidance on training motor skills suggested that physically guiding a movement will impair motor learning, since it changes the input-output relationship for the learned task [8]. Even though it reduced performance error during training, haptic guidance hampered the learning process [9]. Subsequent studies showed that haptic guidance that fades as learning progresses may improve learning outcomes since decreasing physical guidance would encourage learning [10], [11], [12]. For instance, an experimental study in [10] showed that children who practiced with fading haptic guidance (via robotic joystick) learned better than children who practiced without physical guidance.

A subsequent work investigated the impact of haptic steering guidance on curve negotiation behavior [13]. 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 drivers and the guidance systems steering actions. Another study demonstrated that haptic guidance caused interference in motor learning which led to a lower motor skill training efficacy [14]. Similar studies investigated the performance of haptic disturbance and concluded that combining haptic guidance and disturbance could improve motor learning [15], [16]. A recent study demonstrated that driving performance with fatigued drivers was significantly improved when haptic guidance was activated [17].

Training subjects to learn and recreate a complex 3-D trajectory is investigated in [18]. Results showed that the haptic plus visual training method outperformed significantly the visual-only and haptic-only methods. An open source haptic guidance software named I-TOUCH [19] 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 trajectorys 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 guidance methods 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).

Recent studies led to an emerging evidence that haptic guidance may be specifically useful for learning temporal aspects of a motor skill [20], [21], [22]. Learning a dynamic visuo-haptic tracking task suggested that haptic guidance has positive effects on movement speed and smoothness [22], and better learning of temporal force patterns [7]. These studies show that training with appropriately designed haptic guidance can enhance learning of some motor skills, such as time-critical tasks. However, few studies also found long-term retention effects [23]. Therefore, incorporating haptic guidance in a learning environment for motor skills development must be cautiously designed to provide improved learning outcomes. However, most existing studies have not considered a formal comparison study to evaluate the effects of various forms of haptic guidance on learning motor skills. In this paper, we are interested in pursuing such a study, with a focus on handwriting skills development.

2.2 Haptic Guidance for Handwriting

Several studies investigated the effectiveness of haptic guidance for teaching handwriting in different languages. Haptic-based simulation is applied for teaching Japanese letters [19], [24], [25], Chinese letters [26], Latin letters [27], [28], and Persian calligraphy [29]. For instance, systems that utilize haptic guidance to teach handwritten letters were presented in [24] and [30]. 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 haptic guidance for teaching handwriting to typical children [27] and to children with learning difficulties [31], [32], [33], all focusing on full haptic guidance.

In this paper we present a study consisting of two experiments to evaluate the effectiveness of various haptic guidance methods for improving handwriting skills development. We define the learning outcome as the improvement of the quality of handwriting as measured by a human expert and an algorithmic method. Experiment I compares the effectiveness of full guidance and partial guidance in handwriting skills acquisition. Experiment II examines whether combining full and partial haptic guidance at different stages of the learning process results in improving further the learning outcomes. Both experiments are conducted using the haptic handwriting learning tool presented in our previous work [5]. The tool supports both full and partial haptic guidance. The following hypotheses are examined:

(i) Using merely partial haptic guidance provides improved learning outcomes compared to merely full haptic guidance in handwriting skills developments,
(ii) Full and partial haptic guidance methods are rated highly effective as handwriting learning methods, and both provide a positive quality of user experience, particularly when it comes to emotional responses.
(iii) A combination of partial/full haptic guidance provides improved learning outcomes compared to merely full or partial haptic guidance,

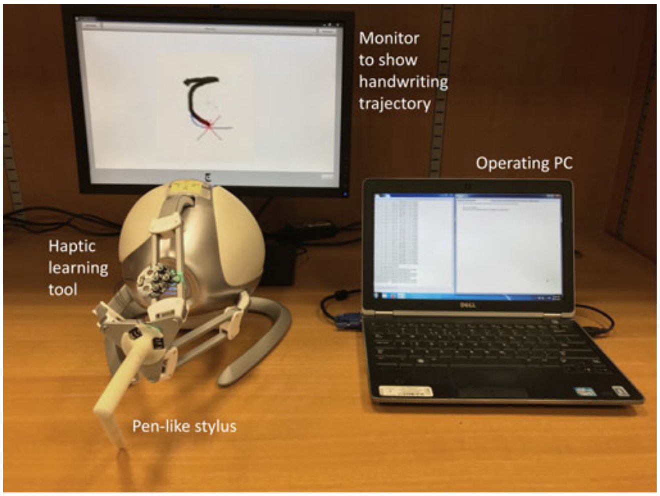

Fig. 1. Experimental setup. The haptic learning tool on the left side is driven by the operating PC on the right side of the figure. The monitor shows the right pathway of the letter and the trajectory of the participant's hand writing.

(iv) When a combination of full and partial haptic guidance (starting with full haptic guidance followed by partial haptic guidance or vice versa) is utilized, the order at which these methods are used is significant.

3 Experiment I: Comparison between Full and Partial Haptic Guidance

3.1 Experimental Setup

The experimental setup includes a laptop, a haptic interface (the Novint Falcon haptic device with a pen-like 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 3,000, 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 [34]. 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. 1.

3.2 Procedure and Evaluation Metrics

A total of 22 adult participants with no previous experience in Arabic language were recruited for this experiment in order to assess and compare the effectiveness of full and partial haptic guidance. Participants were divided into two groups, each one consisting of 5 females and 6 males. The age range was 18 to 45 years. All participants performed the experiment with their dominant hand. None of the participants reported any deficiency in their motor skills. In order to eliminate the effects of unfamiliarity with the experimental setup, the participants were allowed to practice on a few English letters to accustom themselves with the software and hardware setup before conducting the experiment.

The two groups trained, for six sessions, on the same three Arabic letters, shown in Fig. 2, which were selected from different families of Arabic letters. Six sessions are sufficient to show the trend of the improvement in handwriting. An Arabic calligraphy handwriting expert was hired to construct the reference letters. The same expert is also assigned the task of the subjective evaluation of the participants performance at the end of the experiment. Group 1 trained the entire six sessions with the full haptic guidance mode. Equation (1) presents full haptic guidance force calculation where K_{max} is the stiffness of the haptic interface and is equal to 2.31 N/mm and Δu is the displacement. Group 2, on the other hand, trained the entire six sessions with partial haptic guidance. Equation (2) shows how partial guidance force is calculated. In Equation (2), C_p, C_i and C_d are the proportional, integral and differential gains respectively. e(t) is the error between the current position (x_{cur}) and the desired position (x_{des})

Fig. 2. The selected Arabic letters: Jiim (left), Kaaf (middle), and Taa (right). There letters are selected with different families of Arabic letters and recorded by a calligraphy handwriting expert.

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

$$\begin{aligned}\mathbf{F}(t) &= C_p\mathbf{e}(t) + C_i\int_{\Delta T}\mathbf{e}(t)dt + C_d\frac{d\mathbf{e}(t)}{dt}\\ \mathbf{e}(t) &= \mathbf{x}_{cur} - \mathbf{x}_{des}.\end{aligned} \tag{2}$$

The first three sessions were trained on the first day, and the following three sessions were trained on the second day. Successive sessions are separated by at least two hours of break in order to minimize the effects of haptic fatigue and short term haptic memory [35]. In every session, the participants were asked to practice the selected three Arabic letters, 15 times each, using the corresponding haptic guidance mode. The three letters are presented in each session. At the end of each session, participants were instructed to write these three letters using the haptic device in no guidance mode, i.e., they could draw freely on the surface without any assistance from the haptic interface. Once all the sessions were completed, the participants were asked to complete a questionnaire for: 1) describing each haptic mode, 2) evaluating the overall user experience, particularly emotional reactions for valence, and 3) measuring the effectiveness of each haptic mode in improving the quality of handwriting on a 7-point Likert scale.

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 experts letter, then the subject would get a score of 10), and the scores were converted into a scale of 0 to 100. The quantitative algorithmic evaluation (described in detailed in our previous work [5]) is also utilized to provide an objective evaluation of the quality of handwriting performed by the learners.

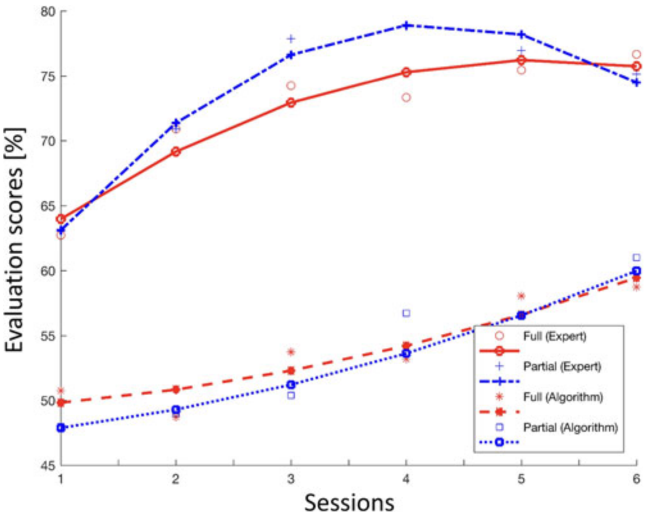

Fig. 3. Evaluation scores of full and partial guidance haptic write learning. Red and blue lines indicate expert and algorithmic evaluations.

3.3 Quantitative Handwriting Evaluation

The haptic learning tool implemented an algorithm to provide quantitative evaluation of the learner performance without any interventions from the instructor (in case the instructor is unavailable). First, all the letters are saved as images and then a number of image similarity measures are considered, which we describe in detail next.

Image similarity metrics match points based on local similarity between images. There are two general approaches, namely, correlation-based approaches and feature-based approaches [36]. 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 [37] transforms an image into a set of features that are invariant to scale. These features are then used to match points in an image. An outlier detection algorithm, random Sample consensus (RANSAC) is utilized to ensure correct matches [38]. 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. Finally, the correlation between the images is calculated as a score in the 0-100 range.

3.4 Results and Analysis

The data gathered for this study are examined in this section. The scores of handwriting quiz right after each training session, as well as the self-reporting questionnaire completed by the end of the last session, are analyzed here. Fig. 3 shows the average scores for the two groups (full and partial guidance) over the 6 sessions of training (with both algorithmic and expert evaluation). Even though improvements in both groups are not statistically significant, both graphs show a steep increase in the score between the first and the last session (around 10 percent of improvement on average for the quality of handwriting). When comparing this improvement with traditional techniques for teaching Arabic handwriting, these results are very promising. For example, Al-Hmouz [39] reported an average increase of 4 percent with traditional learning methods where the author utilized the Letter Sound Fluency measure to evaluate improvement in handwriting. Therefore, it seems that haptic guidance in general (full or partial) is a promising approach for improving learning outcomes of handwriting skills in Arabic language. This confirms previous findings in haptic guidance [21], [32].

However, when comparing full and partial haptic guidance, the differences in learning outcomes are not statistically significant (Wilcoxon Rank Sum test). Therefore, hypothesis (i) is rejected; there is no statistically significant difference in learning outcomes between full and partial haptic guidance.

When it comes to the user quality of experience, participants have rated full or partial haptic guidance method as highly effective (5.65 ± 0.67 for full and partial guidances, Fig. 8). Therefore, hypothesis (ii) is accepted and both haptic guidance methods have resulted in a positive user experience (particularly with high ratings for valence). The differences for effectiveness between full and partial haptic guidance are not statistically significant.

Even though there were no statistically significant differences in rating the valence of full/partial haptic guidance, participants from group 2 (using partial guidance) have consistently provided more positive comments than group 1 (full haptic guidance). This is probably due to the fact that partial haptic guidance is interactive and thus more engaging, since the learner has to construct the handwriting and only when they go off track, the haptic guidance is activated to put them back on the right trajectory.

4 Experiment II: Combination of Full/Partial Haptic Guidance

Handwriting involves developing both gross and fine motor skills. With normal development, fine motor skills are developed from gross motor skills [40]. Existing research demonstrated that full haptic guidance is effective for fine motor skills acquisition due to the ability to reconstruct a precise trajectory for the movement [41]. On the other hand, gross motor skills acquisition is associated with active movements and thus partial haptic guidance may be more effective [42]. Therefore, we hypothesize that early stages of handwriting acquisition, dominated by gross motor skills, is better learned with partial haptic guidance whereas fine motor skills of handwriting are acquired more effectively using full haptic guidance.

Since there were no statistically significant differences in improving learning outcomes for full and partial haptic guidance, in experiment II we examine whether combining full and partial haptic guidance would result in significant improvements in learning outcomes. The experimental setup is the same used for experiment I.

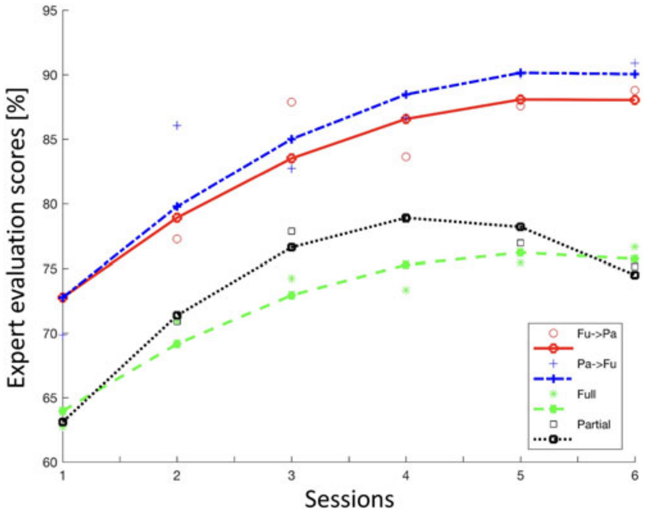

Fig. 4. Expert evaluation scores of the subjects' handwriting. Scatter data points indicate mean score values in each session. Lines indicate second order polynomial curve fitting of mean data points to show the trend of score changes.

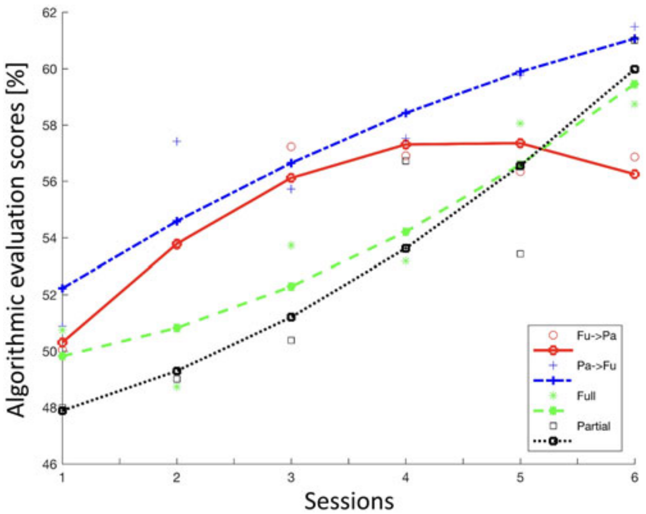

Fig. 5. Algorithmic evaluation scores of the subjects' handwriting. Scatter data points indicate mean score values in each session. Lines indicate second order polynomial curve fitting of mean data points to show the trend of score changes.

4.1 Procedure and Evaluation Metrics

Another 22 adult participants with no previous experience in Arabic language were recruited for experiment II in order to contrast and compare the effectiveness of combining full and partial haptic guidance at different stages of the learning process. Participants were divided into two groups (5 females and 6 males, age range 18 to 45 years): the partial-then-full group trained using three sessions of partial haptic guidance followed by three sessions of full haptic guidance whereas the full-then-partial group trained with three sessions of full haptic guidance followed by three sessions of partial haptic guidance. Participants trained with the same Arabic letters as in experiment I (shown in Fig. 2). This experiment adopted the same experimental procedure used in experiment I, including the evaluation metrics (subjective and algorithmic evaluation).

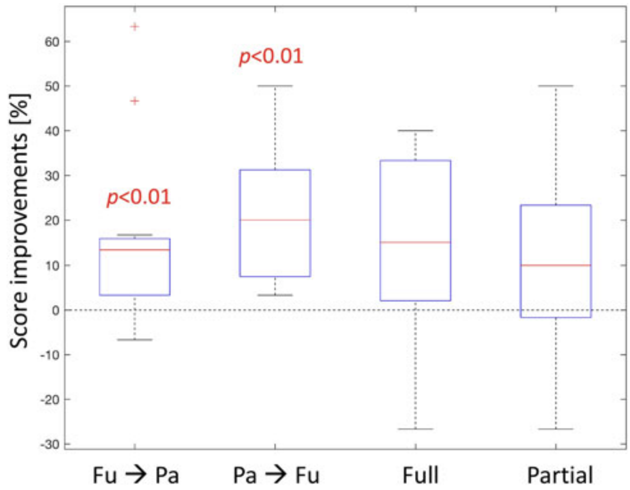

Fig. 6. Improvements in quality of handwriting between the first and the last sessions in expert evaluation score (Wilcoxon signed rank test, $p < 0.01$).

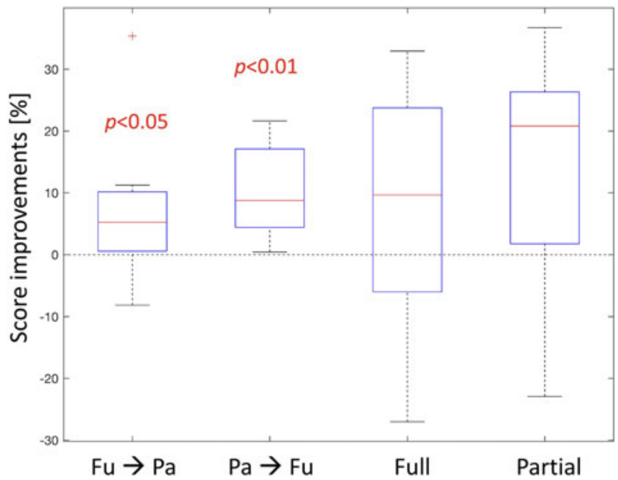

Fig. 7. Improvements in quality of handwriting between the first and the last sessions in algorithmic evaluation score (Wilcoxon signed rank test, $p < 0.05$, $p < 0.01$).

4.2 Results and Analysis

The scores of handwriting quizzes performed by the end of every training session, along with the questionnaires completed by the end of the experiment, are analyzed in this section. Results from experiment I are also used here in order to compare the four combinations of haptic guidance methods: full, partial, full-then-partial, and partial-then-full.

Figs. 4 and 5 show the average scores for the four groups using expert and algorithmic evaluation, respectively. Both figures demonstrate that a combination of full and partial haptic guidance, regardless of the order, outperformed full or partial haptic guidance. Furthermore, Fig. 6 shows that the combination of full and partial haptic guidance resulted in significant improvement in learning outcomes between the first and the last training sessions (16.06 ± 20.88 for full-then-partial haptic guidance, 21.06 ± 15.39 for partial-then-full haptic guidance, 13.94 ± 20.36 for full guidance, and 12.12 ± 21.25 for partial guidance, Wilcoxon signed rank test, $p < 0.01$). However, there is no significant improvement in learning outcomes when merely full or partial haptic guidance are utilized. Similar results are found with the algorithmic evaluation in Fig. 7 (6.82 ± 11.22 for full-then-partial

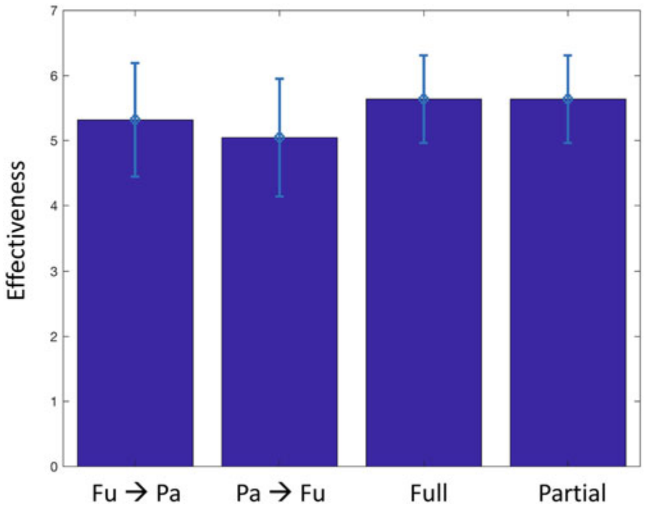

Fig. 8. Mean and standard deviation scores of the participants' response for effectiveness in the end of questionnaire. Kruskal-Wallis test, N.S.

haptic guidance, 10.60±7.48 for partial-then-full haptic guidance, 7.99±18.42 for full guidance, and 13.01±19.22 for partial guidance. Wilcoxon signed rank test, $p < 0.01$, $p < 0.05$). This clearly demonstrates that the combination of full and partial haptic guidance significantly increases the learning outcomes of handwriting skills compared to merely full or partial haptic guidance. Therefore, hypothesis (iii) is accepted. However, there is no significant difference among the score improvements of the four haptic guidance groups in expert and algorithmic evaluation (Kruskal-Wallis test).

Expert evaluation demonstrated that the partial-then-full haptic guidance combination seems to improve further the learning outcomes (around 5 percent more) compared to full-then-partial haptic guidance (Fig. 4). A similar conclusion is derived from the algorithmic evaluation (Fig. 5), with an increase of around 6 percent. Even though these differences are not statistically significant, there are several evidences to accept hypothesis (iV).

Even though there are no statistically significant differences in the effectiveness ratings, it is interesting to observe that participants tend to rate full haptic guidance as the most effective (Fig. 8). This is probably due to the fact that full guidance requires no intervention by the learner when constructing the handwriting task. Participants seem to like this approach the most. However, when examining the quality of the handwriting (both by algorithm and expert evaluation), partial-then-full haptic guidance seems the most effective.

No statistically significant differences in rating the valence of full-then-partial and partial-then-full haptic guidance is reported, as well as with mere full or partial haptic guidance. However, participants have consistently rated the combination of full and partial haptic guidance as highly pleasant (5.91±1.04 for full-then-partial haptic guidance and 5.73±0.79 for partial-then-full haptic guidance). This confirms that both combinations induce positive valence overall.

5 Questionnaire and End-Effector Analysis

5.1 Observations from the Questionnaire

The following observations are derived from the analysis of the responses of participants:

1) In experiment I, one participant in the partial guidance group commented that it would be more effective if the guidance could be decreased as time pass. This is similar to our hypothesis, however the improvement in the partial-then-full guidance is higher than other case in the results.
2) In experiment II, participants are asked to describe how the partial and the full guidance methods work. 90.91 percent of the participants described correctly the two haptic methods (just one participant failed to provide a clear description of each of the two haptic guidance methods), so these two modes are considered perceptually different.
3) Participants have 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 is regarded as useful by 95.45 percent of the participants (with an average score of 5.64 out of 7); and by the same percentage, 95.45 percent, 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 percent of the participants were satisfied (with an average score of 5.78 out of 7) with the haptic learning tool.
4) At the end of the questionnaire, there is a space for comments on how to improve the haptic learning tool. Most participants felt a little confused at the beginning but soon got used to the physical guidance provided by the haptic device. The most common suggestion is to make the 3-D printed pen-like stylus more ergonomic to use (better fit for left and right handed use, triangular shape to ease grip, adjustable for specific hand orientation, etc.). Other participants commented that the screen should be placed underneath the handwriting stylus to emulate intuitive and natural handwriting. It has been somehow distracting to look at the visual display on the screen while handwriting is performed at a different location. Another interesting observation was adapting the stylus for left-handed as well as right-handed learners. One participant mentioned that torque feedback would be useful to align the handwriting stylus in the proper grasping condition—the same grip orientation used by the expert. Another participant suggested to use sensors to measure the stylus grasping properties in order to evaluate and guide a proper holding for the stylus. Another suggestion was to provide direction feedback for where the device is moving. This would help the learner to follow the proper stroke sequence when using full haptic guidance.
5) Comparing partial haptic guidance and full haptic guidance, it seems that when learning the gross aspects about handwriting trajectory, partial guidance is more effective, 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.

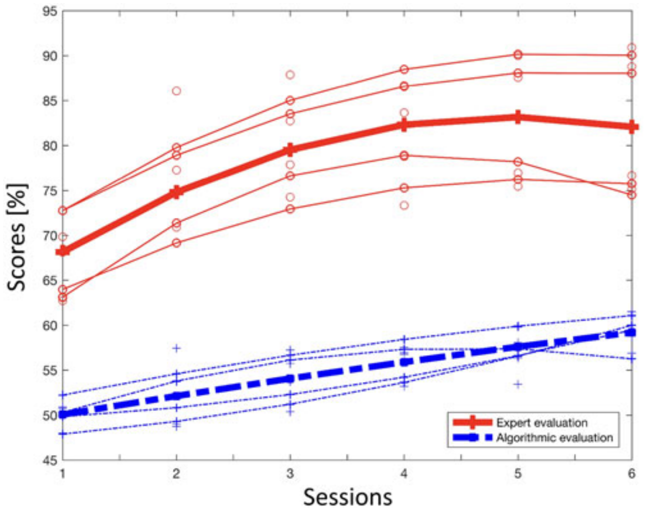

Fig. 9. Grand average of the expert and algorithmic evaluation scores. Thin lines indicate four haptic guidance, and bold lines indicate their average.

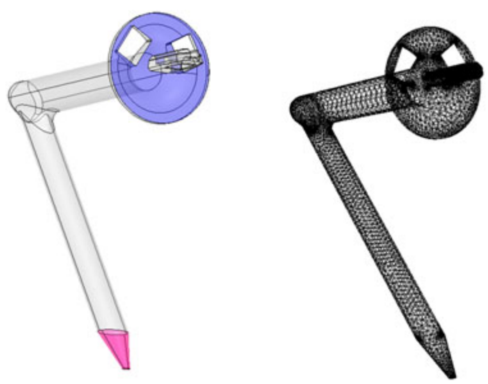

Fig. 10. Left: Dirichlet boundary conditions (pink) and applied force (purple). Right: Meshed object (about 165,000 elements).

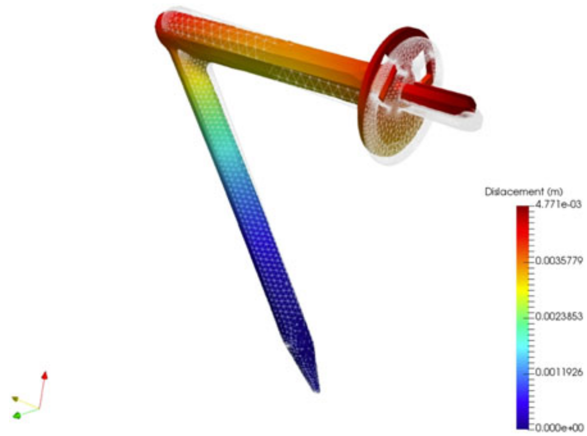

Fig. 11. Maximum deformation simulation for the ABSplus thermoplastic end effector (the shadow object denotes the).

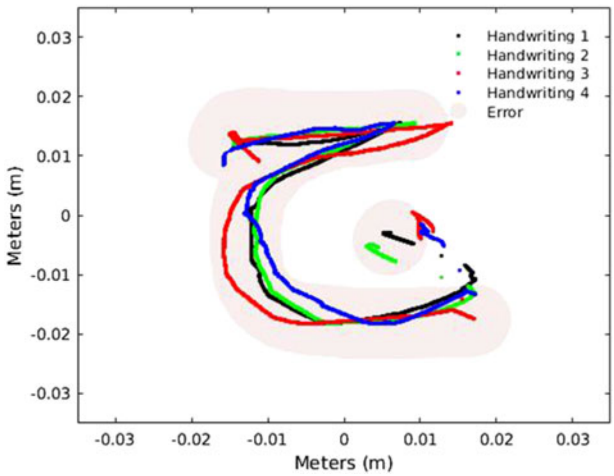

Fig. 12. Verification of simulation through experimental data. The four color lines show the randomly selected participants' trajectories and most of these lines are within the error of the simulation result.

5.2 End-Effector Analysis

An offset of around 20 percent is noted between the algorithmic evaluation and the experts evaluation (algorithm evaluation is lower rated) in Fig. 9. One explanation for this would be that the handwriting expert examined the holistic correctness of the handwriting and therefore tended to give higher grades as long as they are able to read the letters [43]. The evaluation algorithm incorporates fine differences and thus tended to give lower scores. Nevertheless, the trends of both evaluations are similar.

In other words, all the small deviations from the original trajectory of the letter are evaluated by the quantitative algorithm in a negative fashion since they are considered deviations from the desired trajectory. The expert ignored these errors since they are lying within expected margins of handwriting errors.

The working space, the resolution and the dynamic response of the haptic device has been extensively studied by other researchers reporting a sub-millimeter spacial resolution at an update rate up to 1 kHz [44],[34]. Especially close to the center of the working space (where this study took place), the maximum resolution of the haptic device can be found to be 30 encoder pulses per mm [34].

The small variations in haptic guidance are mostly caused by the flexibility of the end effector (geometry and material properties) which causes delays in the response from the time the guidance force is applied from the haptic device until it is displayed at the end effector. Therefore, we present a simulation to evaluate the effect of elasticity of the end effector on the quality of haptic guidance, without taking the human behavior into consideration.

A Finite Element Analysis (FEA) is utilized to examine the effect of elasticity of the tool by performing a linear elasticity analysis with NetGen (meshing) [45], FEniCS (FEA solver) [46], Paraview (post processor) [47]. The maximum force that the haptic device can produce is applied at the matching face of the tool and the conical tip of the end-effector is fixed in place to model the user holding the tool and resisting the applied force (as shown in Fig. 10). The 3D geometry of the tool is meshed appropriately in order to offer a good approximation of the maximum deformation and StratoSys ABSplus [48] filament material properties are used to constitute the material matrix for this simulation.

Simulation results show a maximum deformation of around 4.7 mm due to response delay introduced by the end effector (Fig. 11), which is much higher than the reportded spatial resolution of the haptic device. This means that due to the flexibility of the end-effector user's reaction to the driving force generated from the haptic device might be delayed. Therefore, it is safe to consider the maximum deformation due to the material's elasticity as an error/noise embedded in the produced letters.

In order to validate the simulation results and therefore justify the offset between algorithmic and expert evaluation we follow the following procedure: Four samples of handwriting (of the same letter) are randomly selected and overlaid on top of the reference letter which is extended based on the error that is produced from the simulation, If the simulation is accurate we expect that the handwriting traces fall within the error margins, which is the case as shown in Fig. 12. This means that the evaluation offset is derived mainly from the elasticity of the material.

6 Conclusions

This paper presents a study to evaluate the effects of partial and/or full haptic guidance on the learning outcomes for developing skills in Arabic handwriting. Results show that (1) there is a considerable improvement in the quality of handwriting when using full or partial haptic guidance, however there was no statistically significant difference between full and partial haptic guidance to improve learning outcomes, (2) combining full and partial haptic guidance results in statistically significant improvements in learning outcomes, compared to merely full or partial guidance, (3) partial guidance followed by full guidance is considered to yield the best performance among the four methods of haptic guidance. 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 re-designing the stylus with a stiffer material in order to improve the quality of playback (reduce the errors in reconstruction of a desirable trajectory). Furthermore, we plan to redesign the graphical user interface for use by children, then conduct an experimental study with typical children as well as children with learning difficulties. It would be interesting to investigate whether the conclusions made in this study hold for typical children and/or children with learning difficulties. Another interesting perspective for future work is to investigate the effectiveness of haptic guidance in constructing full words in Arabic, given the fact that Arabic letters have different forms depending on where they appear in the word (beginning, middle, or end of the word).

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