Validating the Performance of Haptic Motor Skill Training

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ABSTRACT

The effect of haptic interfaces on motor skill training has been widely studied. However, relatively little is known about whether haptic training can promote long-term motor skill acquisition. In this paper, we report two experimental studies that investigated the effectiveness of visuohaptic (visual + haptic) interfaces in helping people develop short-term and long-term motor skills. Our first study compared training outcomes of visuohaptic training, visual training, and no-assistance training. We found that the training outcomes for the tested methods were similar when helping participants develop short-term motor skills. Our second experiment assessed the potential of visual training and visuohaptic training in promoting the development of long-term motor skills. Participants were trained during a four-day-long period. The results showed that the participants gained long-term skills through both training methods, and that the training outcomes for both methods were similar. The results also showed that visuohaptic training is a promising method, but that it needs to be further developed to be useful.

KEYWORDS: Haptic training, visuohaptic, motor still, short-term learning, long-term learning.

INDEX TERMS: H.1.2 [Models and Principles]: User/Machine Systems—Human information processing; Human factors; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Evaluation/methodology; Haptic I/O

1 INTRODUCTION

Force-feedback devices have been widely studied, and their applications span from medical simulations to tele-operation systems [1]-[3]. The advantage of providing force-feedback is that it can improve the performance of tasks that required certain motor skills [4]-[6]. A motor skill is a skill that requires effective utilization of muscle, skeleton joints, and limbs of body. Motor skills can refer to actions such as throwing a ball or grabbing a pen from a desk, or to actions as complex as signing one's signature or performing endoscopic surgery.

In recent years, researches have been focused on utilizing haptic interfaces to improve motor skill development [7]-[11], [14], [16]. Normally, motor skills are developed through observation and practice. Motor skills can also be gained by transfer from other people. An example of such skill transfer is teaching children to write. The teacher physically guides the child's hand to show how to write in a correct way. With force-feedback technologies, the physical guiding can be provided in an alternative way, through haptic devices. Instead of having the teacher holding the child's hand, the child can grasp the end-effector of a haptic device, and let the haptic device guide his/her hand through the desired trajectories.

Most of the existing haptic motor-skill training systems seek to transfer experts' skills in a record-and-play manner. In record-and-play, the expert's movements are recorded in terms of positions, velocities, force patterns, and others. Then the recorded movements are haptically and/or visually displayed to learners during the training. Audio information may also be used to provide extra support [13]. There are two playback modes in a record-and-play system, active playback and passive constraint. Both of them are related to haptic display. In the active playback, the end-effector of a haptic device physically guides the learner's hand at a pre-defined speed through a desired trajectory so that the learner can haptically feel the expert's movements through position and velocity cues. In the passive constraint, the learner moves the end-effector through a desired trajectory at his/her own speed. The end-effector movements are constrained to the ideal trajectory in a way that when tracing the expert's trajectory, the learner feels as if s/he is moving along a virtual channel, which keeps the end-effector on the correct path.

With the help of haptic motor-skill training systems, people are expected to gain motor skills through haptic training. However, is still being debated whether haptic training is beneficial for motor skill learning. Many studies have been conducted on this topic, and both positive and negative findings have been reported.

Williams et al. [14] demonstrated that haptic training is beneficial for hand movement learning. Their virtual palpatory diagnosis trainer utilized a PHANToM device [12] to teach students correct hand-movement trajectories in an active playback fashion. They compared the hand movements between two groups of subjects, one of which received the haptic training and the other did not. Their study showed that the trained group performed better than the untrained group.

Avizzano et al. [15] compared haptic training with visual training, and found that haptic training is more helpful for a circle drawing task. The task was simply re-producing a pre-defined circle. With visual training, four critical points on the reference circle were displayed for guiding purposes. With haptic training, a 2DOF force-feedback device passively constrained participants' hands close to the circular trajectory. Results showed that the shapes of the drawn-circles were significantly better after haptic training than after visual training.

Tao et al. [11] investigated the skill-transfer ability of a haptically enhanced Chinese learning system, which was developed to teach Chinese pen-writing and brush calligraphy. Metrics such as character shape, strike smoothness, normal forces against a virtual paper, and pause-and-go motion – all important skills of Chinese calligraphy – were measured to assess post-training performance. The results showed that most of the metrics, with the exception of the normal force pattern, were improved immediately after the training.

In contrast to [11], Morris et al. [19] demonstrated that force patterns were learnable through haptic training. In their study, participants' hands were actively guided along randomly chosen paths. The normal force against a horizontal virtual plane was displayed haptically, visually, or visuohaptically. The study

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revealed that force patterns could be learned through haptic training. Furthermore, visuohaptic training was shown to be the most effective method for force pattern training.

Srimathveeravalli et al. [18] also found that the force patterns could be learned through haptic training. In their study, participants were trained to reproduce an expert's handwriting in terms of shape and force pattern. The reference characters were visually displayed. The expert's position trajectories and the writing forces were passively displayed by a PHANToM device. Findings confirmed that haptic training was helpful for recalling a sequence of force information. However, the study also showed that haptic guidance did not promote character-shape learning.

Similar to [18], Solis et al. [17] did not find haptic training beneficial for motor learning. They evaluated the skill-transfer ability of a Japanese character learning system [16] under three training methods: visual-alone, haptic-alone, and visuohaptic. Task completion time, overall correction force magnitude, and character shape were used to measure pre- and post training performance. Results showed that haptic-only training can only improve task completion time. However, training with both visual and haptic feedback could dramatically improve participants' motor skills. A similar result was found by Feygin et al. [20], who concluded that haptic-only training was effective with respect to the temporal aspect of the task, while motor skill improvements were more due to the training with visual information.

In spite of these different results, one common finding reported in the cited literature was that visuohaptic training was the most effective training method for motor skill acquisition. However, the success of skill transfer was mainly reported immediately after the training. In fact, just-acquired motor skills can be lost rapidly in absence of haptic assistance, even after an intensive training phase [21]. Note that continuously practicing a desired task in a long-term period is believed to be a practical way to gain permanent motor skills. It is also a conventional way that people have used to learn various motions. Fitts [22] defined three phases of learning: 1) cognitive 2) associative 3) autonomous. The cognitive phase is the stage where people gain understanding of what is required. In the associative stage, people learn know how to execute a movement. Finally, in the autonomous stage, people can master the task. Research has shown that haptic training is effective in helping people transfer from the cognitive stage to the associative stage. There is, however, no evidence showing that haptic training can improve the process of learning by promoting skill transfer from the associative stage to the autonomous stage.

In this paper, we report two studies that were conducted to investigate the effectiveness of haptic training in motor skill development. In our first study, we measured the training outcomes of three training methods, no-assistance training, visual training, and visuohaptic training. Short-term skill gains were measured to compare the effectiveness of the tested training methods. In our second study, we conducted a 5-day-long experiment to measure the skill transfer ability with haptic (visuohaptic) training and with visual training, in long-term motor skill development. The findings of these two studies help us gain insights into motor skill learning.

2 EXPERIMENT 1: SHORT-TERM MOTOR SKILL LEARNING

2.1 Participants

Twelve participants from the University of Alberta participated in this study. The group consisted of 3 women and 9 men between the ages of 20 and 27. All of the participants reported normal sense of touch and vision, and all of them were right-handed. The experiment took about 45 minutes. The participants were informed about the purpose of the experiment, procedure, benefits, possible risks, and their rights. The University of Alberta Faculties of Arts, Science & Law Research Ethics Board approved this study; and every participant signed a consent form prior to performing the experiment.

2.2 Apparatus

Haptic guidance was provided by a PHANTOM Omni haptic display device. The PHANToM was placed 38cm horizontally away from subjects' shoulder. Visual feedback was displayed on a 17-inch LCD monitor placed next to the PHANToM in a comfortable distance to participants' eyes. Participants placed their dominant arm on an armrest, which was placed between their shoulders and the PHANToM device. The armrest was 5cm high, 38cm long and 21cm wide. The height of the armrest was sufficient to raise participants' wrists to a comfortable height for manipulating the stylus. A smooth plastic panel was mounted on the far end of the armrest. Participants were asked to hold the stylus of the PHANToM device like a pen and to draw 2D trajectories on the plastic panel just like drawing on a piece of paper with a normal pen. A computer keyboard was placed next to the armrest for participants to control the experiment procedure with the non-dominant hand (see Figure 1).

The test system was developed in C++ using the Open Haptics toolkit from SensAble Technologies [12], and was run on a dual-CPU 2GHz Pentium Dual Core computer with 4G RAM running Windows XP.

Figure 1. Experimental setup.

2.3 Experimental Design

Participants were required to learn three trajectories, triangle, rectangle, and ellipse, under every training method (see Figure 2). We wanted the participants to learn real movements. The reference trajectories were thus drawn by hand by an "expert". The drawings were performed on the horizontal plane. The participants were asked to reproduce the size and the orientation of the reference trajectories as well as the subtle movements made by the "expert". Training was conducted under three paradigms:

1. No-assistance training: No assistance of any kind was allowed in this mode. Learning occurred entirely through

Figure 2. The base trajectories for Experiment 1.

observation and physical repetition.

2. Visual training: Reference trajectories were visually displayed. Participants learned to reproduce the expert's movement by tracing the reference trajectories
3. Visuohaptic training: In addition to the visual guidance, participants' hand movements were physically guided by a PHANToM device.

The study employed a 3x3 within subject factorial design. The training methods (T_n) were counterbalanced

$T_1\ T_2\ T_3$
$T_1\ T_3\ T_2$
$T_2\ T_1\ T_3$
$T_2\ T_3\ T_1$
$T_3\ T_1\ T_2$
$T_3\ T_2\ T_1$

where T_1 refers to no-assistance training, T_2 refers to visual training, and T_3 refers to visuohaptic training. The participants were randomly assigned to one of the 6 order groups. Within each training method, reference trajectories were presented in random order. In order to eliminate confounding, trajectories were rotated by a certain angle when switching between training methods (see Figure 3), on the assumption that changing the orientation of a trajectory will not change its difficulty level for learning. Therefore, 9 trajectories were tested in total.

2.4 Haptic Feedback

The guiding force was generated by the haptic display device in a passive constraint manner. Force-feedback was triggered when the stylus end-effector deviated from the ideal trajectory, and the end-effector was dragged back to the ideal path.

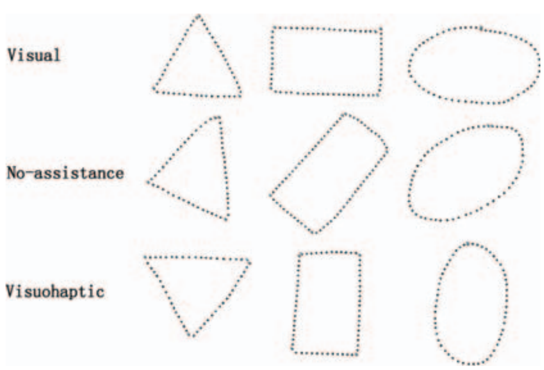

Figure 3. An illustration of order group $T_2\ T_1\ T_3$.

The direction of correction force was calculated by projecting the position of the end-effector onto a sub-trajectory. A sub-trajectory is a segment of reference trajectory that was determined by feature points. The feature points were set where the reference path turned about an angle greater than 45°. For trajectories with more than one sub-trajectory (e.g. the triangle trajectory had 3 sub-trajectories), we projected the end-effector onto the sub-trajectory where the last projection point, p_{last}, was.

Reference trajectories were recorded as series of points described by x, y, and z coordinates. Projecting onto the reference trajectory can therefore be simplified by projecting onto a line segment connecting two adjacent points. Therefore, the correction-force destination could be found by projecting the end-effector onto every line segment of the chosen sub-trajectory, and by searching for a line segment that contained the projection point.

The problem with this approach was if a sub-trajectory consisted of a large number of points, the search process could be resource consuming. Thus, we optimized the process by defining a search window of size w, where w determined the number of line segments to be projected on both sides of p_{last}. In the present study, we chose w to be 5. Therefore, we projected the end-effector only onto the line segments ranging from $p_{last} - w$ to $p_{last} + w$. Note that the range should yield the bounds of the chosen sub-trajectory.

Given the force direction, force intensity was computed by applying Hooke's Law [23], with the stiffness constant set to be 0.8. In addition, damping was added to mitigate buzzing.

2.5 Visual Feedback

Visual feedback was displayed in a graphical region, which consisted of three components: A virtual pen, a drawing box, and two message panels. The virtual pen represented the position of the stylus end-effector in the virtual environment. The drawing box was a rectangular region in the middle of the screen. It displayed the reference and the user trajectories. Participants practiced and reproduced the reference trajectories in the drawing box. In no-assistance training, two drawing boxes were placed next to each other (see Figure 4). The reference trajectories were displayed in the left box, and user trajectories were displayed in the right box. In visual training, a drawing box was used to display the reference trajectory. Participants learned to draw the trajectory by tracing it in the drawing box (see Figure 5). In visuohaptic training, the same visual feedback was provided; in addition, force-feedback was provided by a PHANToM device. In the test trials, participants reproduced the presented trajectory in an empty drawing box. Note that in both, training and testing trials, the start position of a reference trajectory was displayed as a red dot so that the participants were always aware of where to start. The message panels were used to display informational messages. One was placed above the drawing box and the other one was placed below the drawing box. In the training session, the amount of time left was displayed in the upper message panel, and the text flashed during the last 30 seconds of the training.

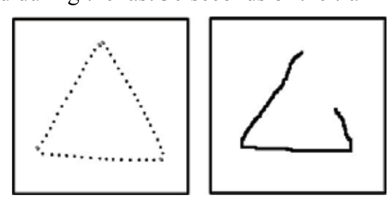

Figure 4. An illustration of no-assistance training. The reference trajectory was displayed in the left drawing box, and user trajectories were displayed in the right drawing box.

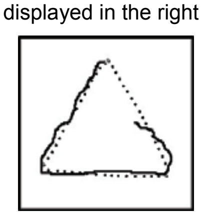

Figure 5. An illustration of visual training. Participants traced the reference trajectory to practice.

To draw a trajectory, participants held the stylus like a pen. They placed the stylus tip on the plastic sheet, which was mounted on the armrest, and moved the stylus on the horizontal plane. User movements were recorded and displayed when the lower button of the stylus was pressed. Before the start of each trial, the PHANToM device pulled the stylus to the start position of the current trajectory to ensure a good start position. At that moment, a "Prepare for a draw" message was displayed right below the drawing box. Subsequently, participants were instructed to press the spacebar to start drawing. The "Prepare for a draw" message was then switched to "Drawing" to indicate that a trial was in progress. Once finished, the participants stopped drawing, and pressed the spacebar to indicate the end of a trial.

2.6 Procedure

Participants practiced in a warm-up session prior to the experiment to get familiar with the training method and the procedure of the experiment. The warm-up session was similar to the actual experiment, except that it was shorter, and lasted only about 10 minutes.

The experiment was organized into 9 blocks. Each block contained 4 ordered phases: 1) presentation phase 2) pre-training phase 3) training phase 4) post-training phase. Switching between blocks or phases was controlled by the spacebar.

In the presentation phase, the participants were presented with one of 9 reference trajectories for 30 seconds. They were required to memorize the trajectory as much as they could. After the presentation phase was the pre-training phase, in which the participants were asked to reproduce the presented trajectory 10 times, as accurately as possible and as fast as possible. After the pre-training phase was the training phase, in which the participants practiced the presented trajectory under one of 3 training methods: no assistance training, visual training, or visuohaptic training. The training phase lasted 3 minutes, during which the participants were asked to focus on the trajectory's critical features, such as shape, size, orientation, and others. The participants could practice as many times as they wanted in the training phase. The post-training phase was presented after the training phase. Similar to the pre-training phase, the participants were required to reproduce the presented trajectory 10 times as accurately as possible and as fast as possible. The experiment finished after 9 blocks were completed. In total, $9 \times 2 \times 10 \times 12 = 2160$ user trajectories were collected for analysis.

2.7 Data Analysis

User trajectories from the pre-training phase and the post-training phase were collected for analysis. Differences between a user trajectory and the corresponding reference trajectory were measured to describe the performance in a trial. In our study, the trajectories to be compared were very similar to each other, e.g. we were always comparing triangles with triangles, and ellipses with ellipses, and so on. Therefore, we describe the difference between two trajectories as the mean deviation between them. To compute the mean deviation, we separated the trajectories into several sub-trajectories bounded by feature points. For instance, an open triangle trajectory has three corners. Therefore, it should have four feature points, two end points and two corners. The feature points separate the triangle trajectory into three sub-trajectories. With the sub-trajectories for both user and reference trajectories, we then computed the deviation between two corresponding sub-trajectories by adding the distances from each sample points on a user sub-trajectory to the corresponding reference sub-trajectory. The mean deviation was then computed by averaging the sums of all the sub-deviations. The ellipse was treated as one piece as it has only two feature points, the start and end positions of the trajectory.

Temporal aspects of the trajectories were not measured in our studies because speed is relatively unimportant in many motor tasks, such as surgery and writing characters or letters, where the correction of hand movement path is of particular importance.

2.8 Results

Mean deviations were computed for each recorded trial. A score for a test trial was calculated by averaging the deviation of 10 trials. The lower a participant scored in a trial, the better s/he

TABLE I
MEAN DEVIATIONS OF PRE AND POST TRINAING UNDER THE TESTED TRAINING MTHODS AND TRAJECTORIES. SKILL-GAIN ARE ALSO SHOWN

		Pre-training	Post-training	Skill-gain
Triangle	No Assistant	3.09	3.16	-0.07
	Visual + Haptic	3.24	2.4	0.84
	Visual	3.69	2.91	0.78
Rectangle	No Assistant	5.77	4.46	1.31
	Visual + Haptic	6.27	5.56	0.71
	Visual	8.25	4.16	4.09
Ellipse	No Assistant	2.06	1.9	0.16
	Visual + Haptic	2.04	1.78	0.26
	Visual	1.92	1.56	0.36

performed in that trial. Participant received one score for pre-training test and one score for post-training test for each of the 9 trajectories (see Table I). The scores were analyzed using an analysis of variance (ANOVA) with trajectory shape, training method, and training effect (performance before and after training) as within-subjects factors.

The ANOVA yielded a significant effect of training, $F(1, 194) = 11.19$, $p < 0.001$; and a significant effect of trajectory shape, $F(2, 194) = 66.79$, $p < 0.001$. There was no effect of training method, $F(2, 194) = 0.5$, $p > 0.05$. There was no interaction between trajectory shape, training method, and training effect, $F(4, 194) = 1.45$, $p > 0.05$, between training method and training effect, $F(2, 144) = 2.09$, $p > 0.05$ and between trajectory shape and training method, $F(4, 194) = 0.87$, $p > 0.05$. However, the interaction between trajectory shape and training effect was significant, $F(2, 194) = 3.95$, $p < 0.05$. This is because the rectangle trajectories dominated the other factors with a high mean deviation of 5.74. Mean deviations for the triangle and ellipse trajectories were 3.09 and 1.88, respectively. The rectangle trajectories were the most difficult to learn, and the high deviation was caused by several factors. First, the length of the edges was difficult to memorize. Second, the orientation of a four-edge trajectory was difficult to follow. Finally, the participants tended to approach short-cuts at the corners, which also increased the mean deviation.

To illustrate the training outcomes, learning curves were generated and assessed for the three base trajectories and for the three training methods. Differences were assessed using paired t-test, which were Bonferroni-corrected for multiple comparisons. Figure 6 shows the learning curves for the triangle trajectory. Mean deviation dropped significantly after the participants had being trained with the visuohaptic feedback, $t(11) = 3.25$, $p < 0.05$. The participants' skills also improved significantly after

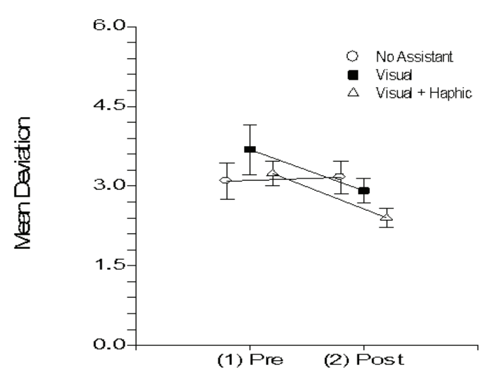

Figure 6. Learning curves of the triangle trajectory. Means and standard errors are shown. For clarity, the data points are shifted along the x-axis.

visual training, $t(11) = 2.61$, $p < 0.05$. However, skills did not improve with the no-assistance training. In fact, user performance dropped slightly after the training.

For the rectangle trajectory (see Figure 7), the participants improved their skill slightly, but not significantly, after the visuohaptic training, $t(11) = 1.88$, $p > 0.05$, while the visual training helped the participants improve their skills significantly, $t(11) = 3.28$, $p < 0.05$. The no-assistance training also resulted in a significant training outcome, $t(11) = 3.26$, $p < 0.05$.

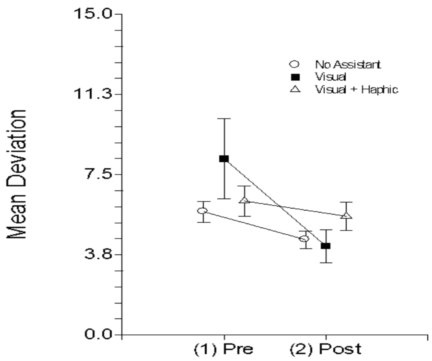

Figure 7. Learning curves of the rectangle trajectory. Means and standard errors are shown.

For the ellipse trajectory (see Figure 8), the participants' skills were improved slightly with all of the three methods. Furthermore, none of the training outcome was significant, $t(11) = 1.52$, $p > 0.05$ for the visuohaptic training, $t(11) = 2.01$, $p > 0.05$ for the visual training, and $t(11) = 0.83$, $p > 0.05$ for the no-assistance training.

The findings suggest that visuohaptic training is beneficial for motor skill learning. However, the advantage of using visuohaptic training is not significant as compared to visual training and no-assistance training (Figure 9). The findings also indicate that training outcome is dependent of the complexity of the motor skill to be learned. For example, the participants made more progress on the rectangle trajectory then the rectangle and ellipse trajectory (Figure 10).

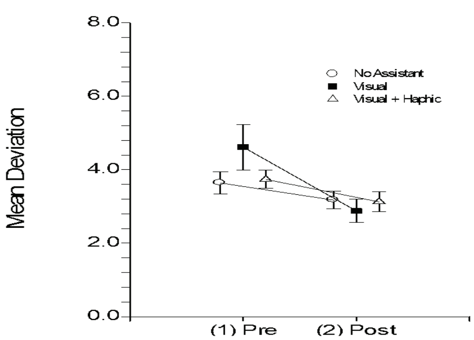

Figure 9. Learning curves of training methods. Means and standard errors are shown.

3 EXPERIMENT 2: LONG-TERM MOTOR SKILL LEARNING

3.1 Participants

Ten participants participated in this study. None of them took part in Experiment 1. The group consisted of 3 women and 6 men

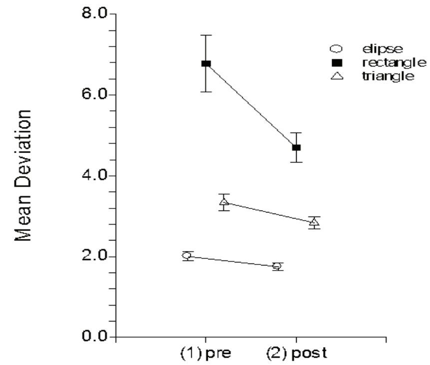

Figure 10. Skill-gain curves for the tested trajectories.

between the ages of 20 and 30. All of the participants reported normal sense of touch and vision, and all of them were right-handed. The experiment took 10 minutes per training day, and lasted for 5 days. The participants received $50 for participation. The participants were informed about the purpose of the experiment, procedure, benefits, possible risks, and their rights. The University of Alberta Faculties of Arts, Science & Law Research Ethics Board approved this study. Every participant signed a consent form prior to performing the experiment.

3.2 Apparatus

The apparatus was the same as in Experiment 1.

3.3 Experimental Design

Participants were required to learn two complex trajectories (see Figure 11), under visuohaptic training and under visual training. We assumed that these two similar, yet different, trajectories had same difficulty levels so that the participants would not spend more or less effort for learning one or the other. The reference trajectories were drawn by an "expert" on the horizontal plane.

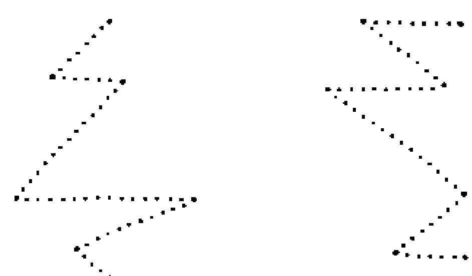

Figure 11. The reference trajectories for experiment 2.

Only visual training and visuohaptic training were studied.

The study employed a 2x2 within subject factorial design. Training methods (T_n) and trajectory shape (S_n) pairs were counterbalanced.

$S_1 T_1$ $S_2 T_2$
$S_2 T_2$ $S_1 T_1$
$S_1 T_2$ $S_2 T_1$
$S_2 T_1$ $S_1 T_2$

Where T_1 refers to the visual training, T_2 refers to the visuohaptic training, S_1 refers to the left trajectory in Figure 11, and S_2 refers to the right one. The participants were randomly assigned to one of the 4 order groups.

3.4 Haptic Feedback

Haptic feedback was the same as in Experiment 1.

3.5 Visual Feedback

Visual feedback was the same as in Experiment 1.

3.6 Procedure

The performance of haptic training in helping people obtain long-term skills was investigated. Therefore, the procedure was similar to the last experiment except that the participants were learning to draw the trajectories over a period of 4 days. Warm-up trials were presented on the first day in order for the participants to get familiar with the system. Ten pre-training and post-training trials were collected on each training day. The 5th day was the final test day, in which the participants were asked to reproduce the reference trajectories without the training processes. As in Experiment 1, an experimental block consisted of four phases, 1) a 30 second presentation of the reference trajectory; 2) a pre-training phase with 10 trials; 3) a training phase; and 4) a post-training phase with 10 trials.

3.7 Data Analysis

Data analysis was done in the same way as in Experiment 1. Mean deviations were calculated for each test trial to describe its similarity to the corresponding reference trajectory.

3.8 Results

The test trials for the first 4 days as well as those collected on day 5 were analyzed to evaluate the performance of the training methods in terms of their ability to promote long-term motor skill development. A score was computed for each, the 10 pre-training trials and the 10 post-training trials. The scores were analyzed using an analysis of variance (ANOVA) with training method, training date, and training effect (pre- or post-training) as within-subjects factors.

The ANOVA yielded a significant effect of training, $F(1, 144) = 8.25$, $p < 0.05$; and a significant effect of training day, $F(3, 144) = 4.68$, $p < 0.05$. There was no effect of training method, $F(1, 144) = 2.7$, $p > 0.05$. There was no interaction between training method, training date, and training effect, $F(3, 144) = 0.44$, $p > 0.05$, between training methods and training date, $F(3, 144) = 0.7$, $p > 0.05$, between training date and training effect, $F(3, 144) = 0.7$, $p > 0.05$, and between training method and training effect, $F(1, 144) = 0.35$, $p > 0.05$.

To illustrate the skill improvement, learning curves are shown for visuohaptic training in Figure 12, and for visual training in Figure 13. The learning curves are very similar to each other. They both have an exponential-decay shape found with motor skill learning, i.e. they both have steep slope at the beginning and a relatively flat slope near the end of the training. Initially, visuohaptic training has a slightly higher deviation than visual training, $t(9) = 1.02$, $p > 0.05$, but it crosses the visual training curve after the second day of training. The participants improved their skills after the 1st day's training but the skill improvement is not significant, $t(9) = 1$, $p > 0.05$ for visuohaptic training, and $t(9) = 1.01$, $p > 0.05$ for visual training. The 2nd day is a turning point for both training methods because the participants' performance did not drop after the 2nd day's training. By comparing the 1st day's pre-training performance with the 3rd day's pre-training performance, we notice that the participants' skills improved significantly, $t(9) = 2.75$, $p < 0.05$ for visuohaptic training, and $t(9) = 2.75$, $p < 0.05$ for visual training. After being trained with visuohaptic feedback, the participants had a mean deviation of 6.16 in the final test, which was statistically similar to the 6.24 received by the participants after being trained with visual feedback, $t(9) = 0.08$, $p > 0.05$. Regarding the skill gain, after being trained with visuohaptic feedback, the participants improved their skills by 5.4, which was higher, but not significantly higher, than the 3.02 obtained with the visual training, $t(9) = -1.19$, $p > 0.05$. In fact, the relatively high skill gain of the visuohaptic training was mostly due to the large variance in the data in the first 2 days. Based on this evidence, we conclude that visuohaptic training was as good as the traditional way of visual training in terms of promoting long-term motor skill development.

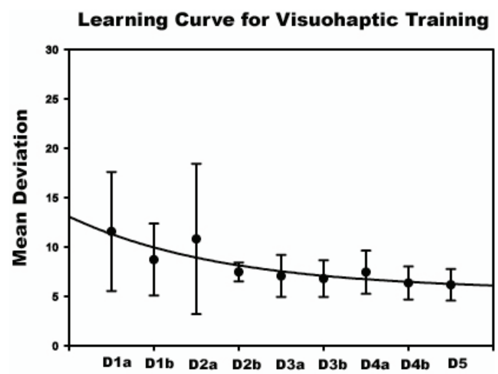

Figure 12. Learning curve for visuohaptic training for 5 days in a row. The horizontal variables "Dxa" refers to the pre-training test on day x, and "Dxb" refers to the post-training on day x. Means, standard errors, and exponential fit are shown.

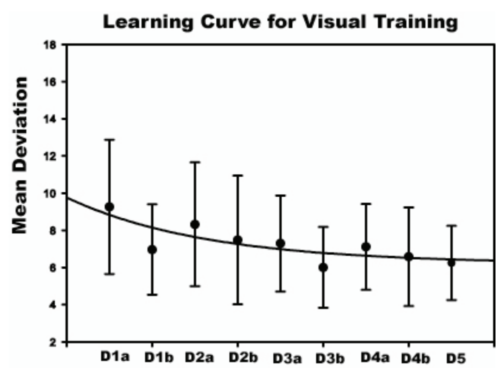

Figure 13. Learning curve for visual training for 5 days in a row. The horizontal variables "Dxa" refers to the pre-training test on day x, and "Dxb" refers to the post-training on day x. Means, standard errors and exponential fit are shown.

4 DISCUSSION

The first experiment revealed that visuohaptic training was as effective as visual training in helping people gain short-term motor skills. In contrast to our finding, Avizzano et al. [15] suggested that haptic-only training was more helpful compared to visual training. One possible reason for the opposite findings was the way visual feedback was provided. In [15], the tested trajectory was visualized with 4 critical points, and these points were the only resource that the participants had during the training. Lack of visual guidance made learning more difficult for their participants. In our study, the tested trajectory was displayed as a series of points, and the participants could trace the entire trajectory. Therefore, adequate visual guidance helped the participants learn better through the training.

As we know, visuohaptic is normally believed to be an effective training method in the sense that it can give learners an idea of how to follow an ideal trajectory. It can also correct wrong movements. However, our study shows that visuohaptic training may not be as good as once thought. It is attractive to many because of its high-tech background and because of features such as error-correction or expert-skill playback. However, it is actually these features that may make training less helpful. Since the haptic device corrects off-track movements continuously learners do not have to correct their movements even when they notice a mistake. In other words, the learners tend to follow the guidance passively, and, as a consequence, they spend less effort on their training and thus learn less. We believe this is a possible reason why the benefit of visuohaptic training proved not significant compared to visual training. However, for motor skill training systems, it is more important to evaluate the ability of promoting the development of long-term skills. This is because the purpose of learning a motor skill is to use it. Visuohaptic training showed some promise in Experiment 2, which showed that the training outcome of visuohaptic training was similar to, but not better than, the training outcome of visual training when helping people develop long-term motor skills. The results of our study showed that there is no significant benefit of using visuohaptic training in terms of skill development. Therefore, we suggest improvements to the current visuohaptic training systems. One possible way to improve visuohaptic training is to encourage active learning. As discussed, the major shortcoming of visuohaptic training is that it discourages effort. It is well known that the more active a learner is, the more efforts s/he tends to spend on learning and the better the training outcome will be. Therefore, motivating learning activities and encouraging effort could be the possible directions to explore.

5 Conclusion and Future Work

The findings of this paper suggest that visuohaptic training is not as effective as once thought. However, the findings also showed some promising result indicating that visuohaptic training could help people develop long-term motor skills. Future work will focus on finding ways to encourage learners spend more effort during visuohaptic training. We are developing a visuohaptic system that can dynamically modify the guiding force magnitude according to learners' skill level. The idea is to provide maximum guidance at the beginning of the training and decrease the strength of the guiding force as the learner's skill is increasing. As the guiding force is reduced, the learner is expected to take over movement control. In the case where the learner needs more assistance, the guiding force can again be increased.

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