Haptic Guidance: Experimental Evaluation of a Haptic Training Method for a Perceptual Motor Skill

David Feygin[1], Madeleine Keehner[2], Frank Tendick[2]

[1] Department of Mechanical Engineering, University of California, Berkeley
[2] Department of Surgery, University of California, San Francisco
{*feygin,mkeehner,tendick*}*@robotics.eecs.berkeley.edu*

Abstract

In this paper we investigate a use of haptics for skills training which we call haptic guidance. In the haptic guidance paradigm, the subject is physically guided through the ideal motion by the haptic interface, thus giving the subject a kinesthetic understanding of what is required. Subjects learned a complex 3-D motion under three training conditions (haptic, visual, haptic and visual) and were required to manually reproduce the movement under two recall conditions (with vision, without vision). Performance was measured in terms of position, shape, timing, and drift. Findings from this study indicate that haptic guidance is effective in training. While visual training was better for teaching the trajectory shape, temporal aspects of the task were more effectively learned from haptic guidance. This supports a possible role for haptics in the training of perceptual motor skills in virtual environments.

Keywords — Haptics, Training, Guidance, Virtual Environments, Motor Learning.

1 Introduction

The training of perceptual motor skills has utilized a variety of approaches. A relatively recent innovation is the use of virtual environments. Although some work has been performed to explore the impact of visual cues on the acquisition of motor skills in virtual environments[1], little research has examined the use of haptics. This paper describes an experiment exploring the use of haptic interaction for the purpose of skill training, which we call *haptic training.* We compare this approach to other forms of training to examine its usefulness for the development of a perceptual motor skill. The proliferation of haptic interfaces within virtual environments makes haptic training a potentially valuable addition to the existing tools in such training environments.

1.1 The Role of Haptics in Training

The underlying processes of relevance to haptic training include mechanisms such as kinesthesis and proprioception, which mediate our haptic interaction with the world. Kinesthesis is the human sense of position and movement, which is created from proprioceptive cues arising from receptors in the joints and muscles. Kinesthesis is crucial in haptic training, because this is the information pathway in the perception of incoming stimuli.

Another important aspect is kinesthetic memory, or the ability to remember limb position, velocity, etc. Clark and Horch have reviewed the research on kinesthetic memory and conclude that humans have a "remarkable ability to remember positions of their limbs quite accurately and for long periods." [2] It is this ability to remember motor patterns that is exploited by haptic training.

Haptic training is different from visual training in the sense that training occurs in body centered, or motor, coordinates as opposed to visuospatial coordinates. This may be especially helpful when learning motor tasks with complex kinematics, where a haptic presentation removes the need for complex sensorimotor transformations. This approach may also be useful for complex, three or more dimensional, motor skills that are difficult to explain and describe verbally or even visually. This may explain why studies have shown that learning is better with physical practice as opposed to observational learning.[3, 4]

Haptic information may also benefit learning when combined with other sensory modalities. Current theories on sensory integration suggest that receiving information from multiple sensory modalities can produce better performance than from a single modality.

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For a long time the haptic modality was considered inferior to vision in terms of perceptual accuracy. The concept of *visual dominance* or *visual capture* placed kinesthesis at a significant disadvantage (e.g., [5, 6]). However, Ernst and Banks found that "the degree of dominance is determined by the statistical reliability of the available sensory information."[7] So, in situations where visual information is unreliable, haptic training may be of increased benefit. Indeed, Kerr found that in some tasks were visual information is not reliable there is a kinesthetic bias.[8] Moreover, most of the literature that focuses on comparisons between kinesthesis and vision examines perception rather than learning. Because learning may depend on different phenomena from perception, these studies apply only to the extent that the given task is perceptual.

1.2 Feedback and Learning

In the motor learning literature there is concern about becoming dependent on feedback, harming performance during the actual task.[9] Although a subject may be able to perform the skill, long term retention of the skill may be reduced due to reliance on external cues. This is a valid concern, especially when using haptic training strategies, as the feedback arising from these methods could breed dependence. However, haptic training strategies may still promote long term learning provided that appropriate measures are taken.

Fitts defined three phases of learning: cognitive, associative, and autonomous.[10] The cognitive phase is the explanatory stage of learning, were subjects acquire an understanding of what is required. In this initial stage of learning, especially with a complicated motor task, haptic training may significantly improve learning by allowing the subject to more easily make a connection between the verbal instruction and the motor requirements. The associative stage is when the subject determines "how" to execute the motion or the task at hand. Haptic training may also help during this second stage of learning by directly showing the subject how to accomplish the task. The third, or autonomous, stage of learning is when the subject has mastered the task and it has become automatized. Haptic training may not be effective during this third phase, since any form of additional or augmented feedback could be detrimental to the final goal of the task becoming autonomous. Thus, haptic training could accelerate and improve subjects' progress through the first two stages of learning.

Another perceived drawback of haptic training is that learning occurs passively. That is, the subject is not actively performing the skill. Passive learning is in general not as good as actively performing the skill, making errors and developing strategies to accomplish the task.[11, 9] However, retention characteristics of active movement can be similar to those of passive movement.[11] It may be possible to develop haptic training strategies that force the subjects' active participation and attention and thus promote learning.

1.3 Approaches to Skill Training

Relatively little research has been carried out to examine haptic training. The studies that are relevant did not produce conclusive results. Yokokohji et al. [12] proposed various haptic training methods, such as guiding a subject through a motion or restricting a subject's motion, using the "What You See is What You Feel" concept. The authors also discussed the possibility of using expert strategies in a record-and-play paradigm.

The "Virtual Teacher," developed by Gillespie et al.[13], used the paradigm of a teacher physically guiding the trainee's motion. They attempted to train humans to do optimal control of a dynamical system. Their results were inconclusive, although they did indicate that some subjects attempted the strategy that was presented by the training. This skill was likely too difficult for novices, and therefore probably not a good test of haptic training. This work underscores some of the difficulties with skill training.

Mussa-Ivaldi and Patton proposed another method for training motion with haptics. They studied the phenomenon of human adaptation to force fields.[14] Once the central nervous system (CNS) has adapted, the removal of the force field causes subjects to produce the desired motions when they attempt to make straight line motions. However, these after-effects tend to disappear after relatively short periods outside the force field as the CNS reverts back to its original state. This task seems more of an adaptation phenomenon, rather than actual learning. This would be a viable haptic training strategy only if these after-effects could be made relatively permanent.

Most virtual environments simulate the real world so that one can practice already-learned skills. These skills are, in general, taught by human trainers. There exist a few virtual environments that do incorporate skill training through the use of visual cues. Todorov, Shadmehr and Bizzi demonstrated that, with a visual virtual environment of adequate fidelity, properly chosen task, and skill training, practice and training of a relatively difficult motor task in a virtual environment could transfer, or even be superior to practice

Figure 1: Experiment in progress. Visual (left), haptic (center), and haptic + visual conditions.

and training on the actual task.[1] They used augmented feedback and an expert strategy to facilitate the learning of a table tennis stroke in the virtual environment and found that this form of training was superior to real-world training. The authors claimed that transfer to the real-world task was largely due to the importance of timing; once the timing aspect of the task was removed from the virtual environment, transfer to the real environment all but disappeared. Our work explores similar training paradigms, but in the realm of haptics.

1.4 Haptic Guidance

The first step in the analysis of the haptic training paradigm is to determine if haptic training promotes learning. We devised an experiment to compare the effects of a haptic training method relative to visual training. The experiment examined the effect of *haptic guidance* on the performance of a perceptual motor skill. Haptic guidance is an extension of the original idea of guidance from previous motor learning literature.[9] In the haptic guidance paradigm, the subject is physically guided through the ideal motion by the haptic interface, thus giving the subject a kinesthetic understanding of what is required. Compared to the earlier guidance methods, this provides a flexible and objective guidance implementation and also the possibility of coupling haptic guidance with virtual environments. The experimental design and results of the experiment, comparing haptic guidance with visual training for learning a complex 3-D trajectory, are described in this paper.

2 Methods

2.1 Experimental Design

The experiment compares three training methods (Figure 1). The first is visual training (V), in which the subject watches the end effector of a manipulandum move through the ideal motion. The second is haptic guidance (H), where vision of the apparatus is blocked while the subject holds on to the end effector and his/her hand is guided through the correct motion. In the final method, haptics plus vision (H+V), the subject watches the motion while also being haptically guided through it. For each training method, there are two possible recall scenarios. Recall of the motion can be performed with direct vision (H+V) or with no vision (H). Note that because the subject controls the manipulandum during recall, haptic feedback is always available.

A 3 x 2 repeated measures design was devised for this experiment. The within-subjects factors were training mode (H, V, or H+V) and recall mode (H, or H+V). Each training mode was combined with each recall mode, creating 6 training-recall combinations. Participants were tested under each of the 6 conditions with the order counterbalanced using a balanced Latin square design. To preclude transfer of learning between conditions, a stimulus pool of 6 different movement trajectories was devised, and each condition was assigned a different trajectory. These combinations were varied systematically across subjects using a balanced Latin square design.

2.2 Target Task

The task for the experiment was a perceptual motor learning skill. The subject was required to learn a complex 3-D motion lasting approximately 10 seconds. This motion was a combination of 3 sinusoids

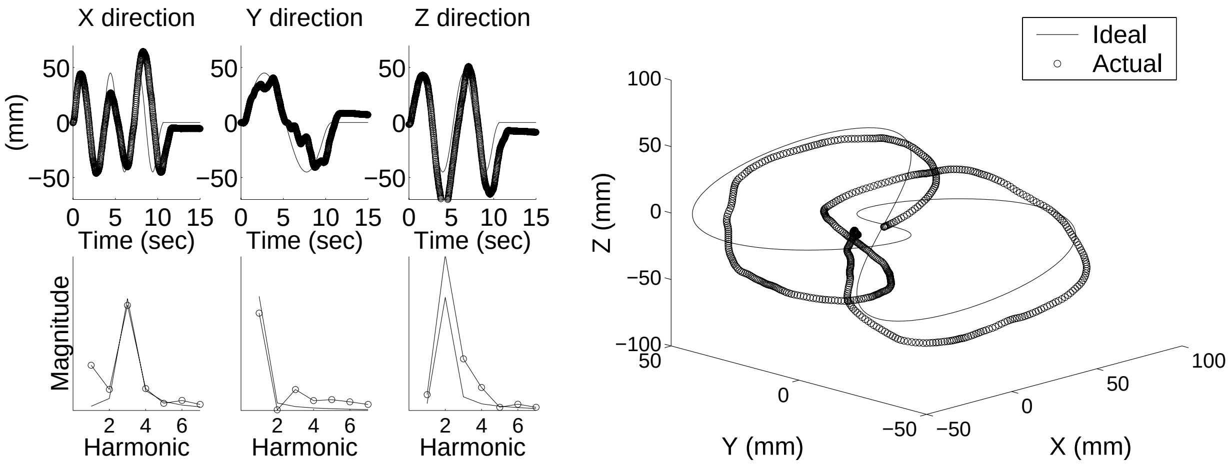


Figure 2: Ideal and actual trajectory: parametric view (left) and 3-D view (right)

of spatial frequency 1, 2 and 3 (corresponding to 0.1, 0.2, and 0.3 Hz) and 4.5 cm amplitude in three orthogonal directions. The motion started and ended at the same point. The velocity of the motion was linearly increased for the first 0.5 seconds and linearly decreased for the last 0.5 seconds to produce smooth acceleration and eliminate discontinuities in velocity that would be impossible to reproduce.

Figure 2 (left) shows the ideal trajectory along the x, y and z directions as a function of time, along with an experimental trajectory. Also shown are the corresponding Fourier transforms. Figure 2 (right) shows the 3-D view of the ideal and an experimental trajectory.

Five additional trajectories of similar difficulty were obtained from this basic trajectory by rotating the first trajectory around two fixed coordinate frame axes and/or inverting the first trajectory. Pilot and experimental subjects reported being unaware that the trajectories were similar.

2.3 Apparatus

The Phantom from Sensable technologies was used as the haptic interface. Additional measurement electronics and upgraded power electronics were interfaced to achieve suitable performance for the experiment.[15] The measurement electronics provided superior velocity estimation, while the upgraded power electronics allowed a smoother feel and increased gains. We used an SGI Octane to control the Phantom and run the experiment program. The haptic feedback loop ran at 1000 Hz while actual and ideal position and velocity were recorded at 50 Hz.

The Phantom has low inertia, backlash, and friction, reducing the mechanical effects of the interface. The subject contacted the interface through a custom low-friction ball joint. This was used to eliminate the additional 3 degrees of orientation that would otherwise be present with a stiff interface. The Phantom was oriented as shown in Figures 1(a)-(c). The Phantom and ball-joint interface were counterbalanced to minimize the effect of gravity.

Haptic guidance was realized with simple proportional-plus-derivative (PD) feedback control of the error between the current and ideal trajectory. The position and velocity gains were set to 0.35 N/mm and 0.0012 N-s/m. This position gain was chosen to be significantly (30%) below the marginally stable gain for the entire workspace. The velocity gain was adjusted to be the dominating force felt by the user during replay. This effectively concealed the small inertia and static friction of the Phantom.

2.4 Procedure

Participants were 36 right-handed volunteers (21 males, 15 females) aged 18 to 44 years. All subjects were students attending the University of California, Berkeley, and were paid for participating.

Verbal instructions were issued, and a familiarization period comprising 3 practice trials was given to demonstrate the 3 possible training modes and 2 possible recall modes. Following the practice trials testing began. Each experimental trial consisted of a training phase and a recall phase. The training phase comprised two consecutive presentations of a trajectory. This was immediately followed by the recall phase, in which the participant was required to reproduce the motion just presented as accurately as possible in terms of both pace and position.

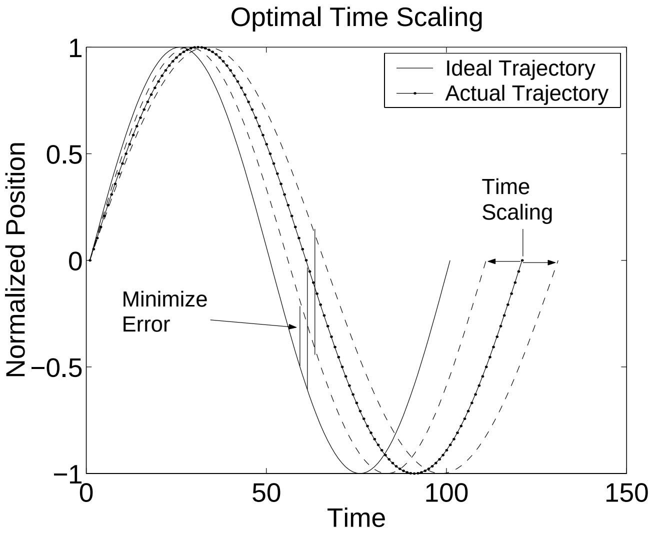


Figure 3: Determining optimally linearly scaled position error.

This sequence was repeated 15 times for each condition, with the same training-recall combination throughout all 15 trials. These were separated into 3 smaller blocks to allow a short rest after every 5 trials. A 5 minute break separated each block of 15 trials. Testing was conducted over two consecutive days to reduce fatigue.

2.5 Data Analysis

Four measures of performance were used: position accuracy, shape accuracy, timing accuracy, and drift accuracy. Only the data from the recall trials were analyzed.

The collected data were preprocessed to eliminate experimental artifacts. The data were filtered at 2.5 Hz. The distance between the target end position and the position at which the subject stopped moving was defined as the "drift error." The drift was assumed to increase linearly with time from the beginning of the motion to the end. This linear equation of drift was subtracted from the motion data before analyzing position error because drift was not relevant to determining whether the subject had learned the desired motion.

To examine position accuracy, we eliminated time dependence by optimally linearly scaling the actual data in time to minimize the total integrated position error along all dimensions simultaneously. Figure 3 illustrates this process.

Shape accuracy was measured using elliptic Fourier analysis.[16] This analysis looks at the spatial frequency in each dimension. That is, the zeroth harmonic is the DC offset, the first harmonic has spatial frequency 1 (or temporal frequency 0.1 Hz), etc. The Fourier transform of the ideal trajectory consists of a single harmonic in each of the three directions; the remaining harmonics are of zero magnitude. The transforms of the ideal trajectory and a sample experimental trajectory are shown in Figure 2(a).

Once the data were transformed into the frequency domain, it was possible to compare the phases and magnitudes of the ideal and actual harmonics. Although we tried a number of ways to compare the harmonics, for the sake of brevity we present only one, which we call the "correct harmonic analysis." This measure provided insight into whether the subject had grasped the basic structure of the motion. If the largest magnitude harmonic in the actual motion was the same as the largest harmonic in the ideal motion, the trajectory received 1 point. Since there were three axes, the trajectory could receive a score from 0 (if none of the axes had the correct fundamental harmonic) to 3 (if all axes had the correct fundamental harmonic). In Figure 2, the subject scored a 3, since all of the axes had the correct fundamental harmonic.

The timing or pace error was taken to be $(1-(SF))^2$; where SF was the scaling factor from the optimal linear scaling analysis.

3 Results

3.1 Learning Curves

Figure 4 shows the optimally linearly time scaled position error, averaged over the 36 subjects, for each condition. All conditions showed significant performance improvements between the first and the last trial, using a paired t-test ($P < 0.001$).

The performance curve for the correct harmonic analysis had similar trends to that of the position error performance measure. This measure also showed statistically significant performance improvements for all conditions ($P < 0.001$).

No significant learning occurred for either the time scale error or the drift error on any of the experimental conditions.

3.2 Comparison of Final Performance

When comparing the final performance in each of the six conditions, we first averaged each subject's recall performance over the last set of five trials. For the drift error and time scale error measures, we averaged over the last ten trials, because these errors had

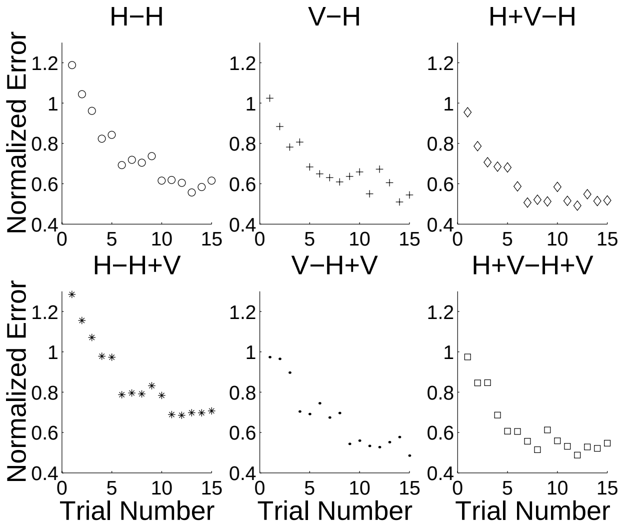


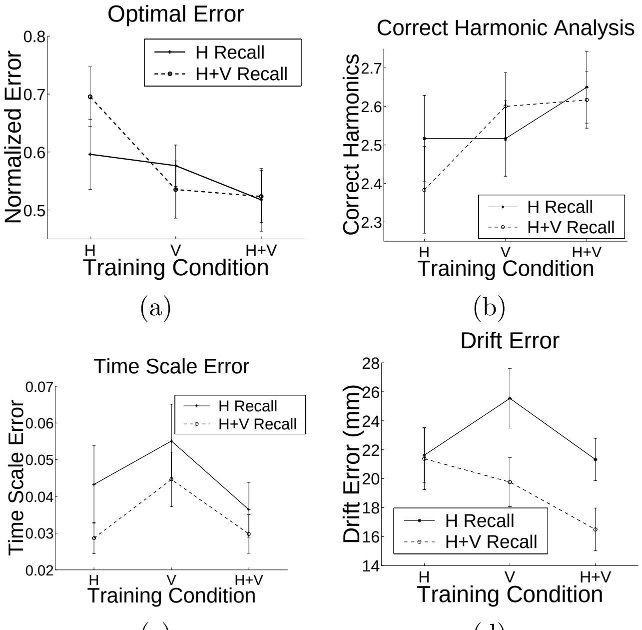
Figure 4: Improvement in optimally time scaled position error over 15 task trials.

stabilized by the second five-trial set. Figure 5 shows these plots. These measures were entered into a 3x2 repeated measures ANOVA using SPSS. The within subjects factors were training mode (H, V, H+V) and recall mode (H, H+V). Multiple pairwise comparisons were performed with the Bonferroni t test.

Figure 5(a) shows the final performance of the optimally time scaled position error for all conditions. A significant main effect of training mode was found ($P < 0.005$), but no main effect of recall mode. The H training condition had significantly poorer performance on this measure of position accuracy ($P < 0.05$) than the H+V training condition, and marginally poorer performance than V ($P < .09$). A 2x2 ANOVA was performed to isolate the H-* and V-* training conditions to examine the interaction between these two modalities. This analysis showed a marginally significant interaction between training mode and recall mode ($P < 0.06$).

Figure 5(b) shows the final performance for the correct harmonic analysis. A significant main effect of training mode was found ($P < 0.02$), but there was no main effect of recall mode. A 2x2 ANOVA comparing the H-* and V-* conditions alone showed a marginally significant interaction between training mode and recall mode ($P < 0.09$).

Figure 5(c) shows the final performance for the timing error. A significant main effect of training mode was found ($P < 0.02$), and a marginally significant main effect of recall mode ($P < 0.08$), with vision during recall benefiting performance. There was no significant interaction between training and recall.



(a) (b)

(c) (d)

Figure 5: Comparison of conditions: (a) optimally time scaled position error, (b) correct harmonic analysis, (c) time scale error, and (d) drift error.

Figure 5(d) shows the final performance for the drift error. A significant main effect was found for both training mode ($P < 0.05$) and recall mode ($P < 0.005$), but there was no significant interaction between the two factors.

3.3 Anecdotal Findings

Subjects described many different strategies for learning the motion. The strategies included songs (mainly for timing), verbal strategies (the words up, down, left, right, etc.), moving their body in concert with the motion, visualization (trying to visualize a trail in space), breaking the motion down into known shapes such as circles or ellipses, segmenting the motion and learning it piece by piece, and trying to remember extreme points in the motion and moving between them.

During conditions when haptic guidance was not used, at least 7 out of the 36 subjects attempted to move their hands in concert with the motion that was displayed. These subjects were asked to keep their hands at their sides. Other subjects moved their torso or head in concert with the motion being presented, which was allowed. This seems to indicate that a motor expression of the task is either natural or helps in the retention of the trajectory. Subjects did not appear to move any part of their body in the haptic or combined training conditions.

4 Discussion

Training mode had a significant effect on all measures of performance. Haptic training alone was less effective than visual training with respect to position and shape measures, but more effective with respect to timing. Recall mode affected only the timing error and drift error measures. Although interaction between training mode and recall mode was only marginally significant for the position error and shape accuracy measures, the fact that interaction occurred for both of these measures that emphasize trajectory accuracy (as well as in other measures which were tested but there is not space to describe here) suggests that this a real phenomenon. It would indicate that the effect of training mode is moderated by the mode of recall required. This effect is mostly attributable to a drop in performance with haptic training when the recall mode includes vision. This suggests that vision may somehow interfere with the haptic representation of the task.

The apparent interference of vision at recall, when training is haptic, relates to previous research. Adams argued that "Vision overpowers proprioception when it is present and degrades proprioception's influence, but proprioception is not potent enough to work conversely and erode the influence of vision."[17]. Indeed, the interfering effect of vision on haptic training may even have been underestimated in the present study, since many of the subjects did not look at the apparatus during the H-H+V condition. Whatever the underlying mechanisms for this effect, this suggests that haptic guidance alone is not an optimal method for training for position or shape accuracy when direct vision is available during the task.

When the effects of haptic guidance and visual training were analyzed separately, we found that position and shape accuracy were dominated by visual training, while timing accuracy was dominated by haptic training. This indicates that whether or not vision is available during the task, haptic guidance improves timing performance. This finding concurs with benefits to timing found in previous research comparing observational and physical practice.[3, 18] Although haptic guidance training was better than visual training for timing accuracy, having vision during the recall significantly improved performance, thus indicating that timing information can be distilled from visual perception.

The particularly powerful effect of recall mode on drift error was probably due to the benefits from having visual feedback during this primarily perceptual task. This is reasonable because percepts about the initial location can be correlated with percepts available during recall. The results of the drift error analysis agree with the findings of Ernst and Banks [7] that when available, two perceptual modalities can be combined to produce increased accuracy.

5 Conclusions

The findings from this study indicate that haptic guidance can benefit performance, especially when training the temporal aspects of a task. Given that timing can be an important aspect of transfer from the virtual to the real environment [1], haptic guidance could aid in training transfer.

The results from this experiment concur with the results from studies comparing observational and physical practice. This implies that haptic guidance may produce similar benefits to physical practice in general (e.g. improving spatial cognition [4]), although conclusions about long-term retention cannot be made from the present study. We plan to study long-term learning in future experiments.

In the future, we hope that haptic training will be used in conjunction with current training methods to train skills beyond simple perceptual motor skills. Our goal is to use haptic training to foster an understanding of complex cognitive and spatial skills.

Looking to future applications, we believe that the haptic virtual environment paradigm can be taken a step further, beyond purely passive simulation, into the realm of skills training. Ultimately, we hope that haptic training will be incorporated into virtual environments along with other training and instruction.

Acknowledgments

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