If we knew what it was we were doing, it would not be called research, would it?

– Albert Einstein, 1879 - 1955.

University of Alberta

A Performance Analysis of Motor-skill Training Using Haptic Training

by

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Abstract

Haptic motor-skill training is getting more and more popular. Relatively little is known about the effects of haptic training on long-term motor-skill acquisition. This thesis reports two experimental studies that investigated the effectiveness of visuohaptic interfaces in helping people develop short- and long-term motor skills. The results show that the visuohaptic training is helpful for motor-skill acquisition, but that it is not as effective as the training with visual-only feedback, which suggests that visuohaptic training needs to be improved to achieve better performance. Two other studies were conducted to investigate the perception of haptic force direction and magnitude. The effects of hand motion and motion speed were measured, and discrimination thresholds for five reference force directions were determined. The results suggest motion speed do not affect the perception of force direction and magnitude. Furthermore, hand motion and force direction affect the perception of force direction but not the perception of force magnitude.

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Chapter 1

Introduction

With the assistance of haptic interfaces, the interaction between human and computer can be improved through the sense of touch. Haptic interfaces are widely used for applications such as medical simulations and tele-operations [64, 54, 1]. Recent studies have shown that haptic interfaces can also be helpful for motor-skill learning [38, 32, 65, 10] and rehabilitation [34, 15, 37, 8, 13, 18]. People use and learn motor-skills in their daily life. A conventional way to learn motor-skills is through observation and practice. The presence of haptic interfaces provides us with a new option for motor-skill acquisition. As a consequence, a variety of haptic motor-skill training systems have been developed [14, 27, 43, 24, 53]. Studies were conducted on the haptic motor-skill training systems to measure the effectiveness of haptic training. However, most of the studies only demonstrated immediate skill improvement. Immediate skill improvement is also known as short-term learning, through which gained skills are maintained by trainees' motor memories in a short-lived brittle form [11, 19]. Ungerleider et al. [59] stated that motor skill learning had two distinct stages, fast learning stage and slow learning stage. In the fast learning stage, trainees' motor skills improve considerably after a short period of training. The gained skills can be lost rapidly in absence of training [33]. Short-term learning happens in this stage. In the slow learning stage, the trainees' motor skills improve slowly after a relatively long period of training. In this stage, gained skills are maintained by motor memory in a long lasting stable form. Learning through this stage refers to long-term learning. The success of long-term learning counts on continuous practice, while, good sleep may also be helpful [39, 61]. As far as we know, no study has been conducted to demonstrate whether haptic training promotes long-term motor learning. Therefore, we conducted several studies to investigate the effectiveness of haptic training in motor-skill development. In our first study, we measured the training outcomes of three 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 experiment to measure long-term motor-skill development with visuohaptic feedback and with visual feedback alone. The findings of these two studies helped us gain insights on of motor-skill learning.

Haptic motor-skill training systems are still in their early stages. Therefore, they can be optimized so as to maximize training outcomes. For instance, most of the existing haptic motor-skill training systems are designed to generate proper force feedback so as to either actively lead the trainee's hand through an ideal trajectory or to passively constrain the trainee's hand movement close to the ideal trajectory. In either case, the guiding force changes its direction continuously. Therefore the trainee is required to be aware of the changes of the force direction in order to keep his/her hand on the right path. When the direction changes are too small to be perceived, visual feedback should be provided to facilitate awareness. However, very little is known about the perception of force direction. Therefore, we conducted the third study to find out the minimum difference between two force directions that people can discriminate during their movement through an ideal trajectory.

It is well known that the more effort trainees put in their training, the better their training outcome will be. Hence another way to optimize the existing motor-skill training systems is to encourage trainees to spend more efforts in their training. In our system for the collaborative training of cataract surgery (HAVE project [14]), we proposed to dynamically modify the guiding force to facilitate learning. The idea is to provide maximum guidance at the beginning of the training and decrease the strength of the guiding force as the trainee's skill is increasing. The trainee is expected to take over movement control as the guiding force is reduced. In the case where the trainee needs more assistance, the guiding force can also be increased. For such a system, it is important to know what force magnitudes are detectable. Therefore, we conducted the fourth study to assess the discrimination threshold of haptic force magnitude.

The rest of this thesis is organized as follows. Chapter 2 discusses the related work. Chapter 3 describes the experiment on short-term haptic learning. Chapter 4 describes the experiment on long-term haptic learning. Chapter 5 describes the experiment on the perception of force direction. Chapter 6 describes the experiment on the perception of force magnitude. Chapter 7 summarizes our findings and proposes future work.

Chapter 2

Literature Review

This chapter provides a general review of pertinent literature relating to our research. Our work mainly focuses on two topics, haptic perception and haptic learning.

2.1 Haptic Perception

Haptic perception includes tactile perception and kinesthetic perception. It involves sensing through skin or through movement of joints and muscles. It is extremely important to understand how people perceive haptic stimuli before haptic-based systems are designed. Among the areas of haptic perception research, perception thresholds are of particular importance. There are two types of perceptual threshold, absolute thresholds and difference thresholds. The absolue threshold refers to the minimum intensity of a stimulus that is detectable. The difference threshold refers to the minimum change in stimulation received to produce a different sensation. Ernst Heinrich Weber [63] observed that most difference thresholds are proportional to stimulus intensity and thus can be expressed as:

$$\frac{\Delta S}{S} = C$$

where S represents the stimulus intensity, ΔS is the difference threshold or just noticeable difference (JND), and C is a constant, called the Weber fraction. In the next few sections, we discuss the perception researches related to our work. First, we introduce the fundamentals of tactile and kinesthetic perception.

2.1.1 Tactile and Kinesthetic Perception

Tactile perception is sensation through touch. It arises from receptors located in the skin. The tactile receptors convey information including pressure, pain, temperature. There are 2 types of tactile perception, passive and active touch. Passive touch refers to the perception arising from the contact of objects with the skin of a non-moving body part. Sensing a bird landing on one's shoulder is an example of passive sensing touch. Active touch occurs when people actively explore objects' properties. Finding a door handle in a dark room is an example of sensing by active touch. When active touch occurs, kinesthetic perception is involved as well. Therefore, muscles, tendons, and joins supply information to the brain. Haptic perception refers to the perception through active touch.

Kinesthetic perception conveys information about limb movement, limb position, and force. Kinesthetic receptors are mostly located in tendons, muscles, and joints. Kinesthesia is a key component of motor tasks. For example, operating in a surgery requires a fine-tuned sense of the position of joints. This sense can become automatic through training. Researchers have demonstrated that kinesthesia-based haptic perception relies on the forces perceived during active touching [44]. Therefore, the creation of virtual shapes is possible by using different haptic forces.

The central nervous system (CNS) is responsible for motor control and motor learning. Sensory receptors in skin, muscles, joints, and tendons receive stimuli, and transmit to the CNS through sensory nerves. Sensory nerves terminate in the spinal cord and the brain, which are the two major components of the CNS. The spinal cord contains motor neurons and central pattern generators (CPGs). The CPGs generate motor commands that trigger rhythmic behaviors (e.g. dancing), and the motor neurons send motor commands to muscles via motor nerves.

The brain is composed of forebrain (telencephalon and diencephalon) and brainstem. Furthermore, the brainstem consists of hindbrain (medulla and pons) and midbrain. Similar to the spinal cord, the brainstem also has motor neurons, sensory nerves, and CPGs that contribute the motor control. In addition, the superior colliculus and the red nucleus in the midbrain are responsible for motor control. In forebrain, the cerebral cortex and the basal ganglia in the telencephalon as well as the thalamus and the hypothalamus in the diencephalon play a significant role in motor control. The thalamus receives inputs from exteroceptive receptors, as well as input from the superior colliculus, and transmits them to the cerebral cortex and basal ganglia. The hypothalamus is responsible for the output of the CNS, which includes neuroendocrine, instinctive behaviors, and autonomic outputs.

2.1.2 Haptic Perception of Surface Characteristics

In haptic research, a commonly used haptic device [56] has a stylus that interfaces the virtual and real world. Users hold the stylus like a pen, and explore the virtual world with the stylus tip. Object characteristics such as shape and texture are perceived by striking the tip across a virtual surface using a constant penetration force [60]. Cholewiak and Tan [17] measured detection thresholds for virtual surfaces with sinusoidal and square wave gratings. The thresholds were evaluated as a function of the spatial frequency of the waves. The study revealed flat-U-shape threshold curves. It has been shown that the perception threshold of a virtual texture obtained indirectly by a grasped stylus is higher than the one of a real texture perceived by user's finger tip [28, 51]. Although, surface texture is the main factor that affects the perception of roughness [45], rigid tools (e.g. a stylus), which are placed between the user's skin and a virtual texture, can also impair perception. Sylvester and Provancher [50] addressed the problem by adding an extra layer of physical interface, which provided skin stretch to user's finger tip. In their system, kinesthetic resistance was provided through a PHANToM device to user's index finger. Skin stretch was provided by a thimble tactile display, which simulated the direct contact between finger tip and virtual surfaces.

The perception of surface roughness can also be affected by visual feedback, probe radius, and texture element spacing. Poling et al. [42] studied the effects of visual feedback on the perception of surface roughness. They measured roughness thresholds under three conditions of feedback, haptic, visual, and visuohaptic. Force feedback was provided by a PHANToM device. Their findings suggested that visuohaptic assistance significantly decreased the perception threshold. Furthermore, the study revealed that visual channel dominates the perception of roughness if two surfaces are visually distinguishable. Unger et al. [58] studied the relationships between probe size and texture element spacing using JND as a metric. Their findings showed that the JND's of texture roughness varied based on the choice of probe size and texture element spacing. When probe size is fixed, the JND decreases as texture spacing is increased; when texture spacing is fixed, the JND increases as probe size is increased.

Most haptic devices provide a physical interface that can be held by hand. It has been shown that the shape of grasped tools might not affect the perception threshold. Israr et al. [25] measured the minimum intensities of tangential vibrations that could be sensed by hand through a grasped vibratory stylus. The stylus shook along its length in sinusoidal waveforms. To ensure the vibrations to be tangential to the skin, the stylus was required to be held in a way similar to holding a pen. A U-shape threshold curve was found from seven reference stimuli with frequencies ranging from 10 to 500Hz on an equally spaced logarithmic scale except for the last stimulus. A similar threshold curve was found in the authors' later research [26] with similar experimental settings except that the stylus interface was replaced by a vertical vibratory ball. Results from these researches showed that the threshold curves of tangential vibrations remain independent of the shape of physical interfaces.

2.1.3 Haptic Perception of Torque

Yang et al. [66] measured torque thresholds by discriminating between smooth and rough turns of a rotary switch. In their study, each trial consisted of turning a switch knob twice. For each turn, the subjects felt either a smooth sinusoidal torque profile or one with noise. The thresholds were evaluated as a function of the spatial period of sinusoidal variation. Results showed that discrimination thresholds increased as the spatial period of stimulus increased.

2.1.4 Haptic Perception of Force Direction

We are particularly interested in the perception of force direction because our research on haptic motor-skill training system requires a solid understanding of how humans perceive the direction of a guiding force. The threshold of force direction can help us optimize the existing motor-skill training systems to help trainees to achieve better training outcomes.

Astrid and Jan [9] demonstrated that humans have the ability to sense and reproduce haptic orientations. In their study, participants were asked to sense the orientation of a reference bar by their dominant hands. The participants were then required to re-orient a randomly oriented test bar to make it parallel to the reference bar. The reference bar was placed in one of the four orientations: 0°, 45°, 135°, and 90°. Both reference bar and test bar were placed on the horizontal plane. The study showed that the participants performed better at orientations of 0° and 90° (with respect to the sagittal body plane) than at 45° and 135°. The authors stated that the performance impairment was due to the oblique effect.

Toffin et al. [57] asked the participants to sense forces generated by a joystick. The reference force directions were distributed uniformly around a circle on the horizontal plane. The participants were asked to resist the force by holding the joystick constantly at the central position until they felt they had achieved a good perception. A variable direction test force was subsequently generated by the joystick. The participants then rotated the joystick to re-orient the test force to the same direction as the initial reference force. The study showed that human could discriminate forces with a difference of ±30°.

Differences between force directions can be too small to be detected. This may cause problems to some applications (e.g. the motor skill training systems). If this is the case, additional feedback should be provided through other sensory channels. Therefore it is desirable to evaluate the smallest perceivable difference of force direction.

The smallest perceivable difference of force direction is also known as the difference threshold (discrimination threshold) of force direction, which has only been studied in recent years. Barbagli et al. [12] assessed the discrimination thresholds of haptic force directions for five reference force directions, 0°, 45°, 90°, 135°, and 180°. In their between-subject study, the participants were instructed to sense the forces by holding the thimble of a PHANToM device at a constant position using their index fingers. The task was to discriminate a variable-direction test force from two identical reference forces. The study reported a discrimination threshold of 25°. It was also found that visual cues significantly affected the perception of force direction, while force direction did not affect the discrimination performance.

To confirm that the perception of force direction is not affected by force direction, Tan et al. [52] conducted a similar study using with-in subject design. The discrimination thresholds of force direction were determined on participants' steady index fingers for five reference force directions, the same directions as tested in [12]. The study showed that the perception of force direction is not affected by the reference force direction. Furthermore, the authors stated that the discrimination threshold of force direction ranged from 25° to 33°.

The reported thresholds were obtained without hand or finger motions. In real world applications, however, hand motions are usually necessary for exploring a virtual environment or for performing certain tasks (e.g. in motor skill learning). It is thus important to know if and how hand motion affects the discrimination of force direction. To the best of our knowledge, no such study has been conducted so far. Our study on force perception addresses this issue. We will discuss the details in Chapter 5.

2.1.5 Haptic Perception of Force Magnitude

In the ongoing HAVE project [14], we proposed to optimize the existing haptic motor-skill training systems by dynamically changing the intensity of guiding force so as to encourage trainers' efforts. Therefore, it is necessary to understand how humans perceive force magnitude.

There are a number of papers that investigated human perception of force magnitude. Findings are reported mainly in the form of difference thresholds. Allin et al. [7] assessed the sensitivity to haptic force magnitude applied to the index finger. The force was applied tangentially to the index finger's semicircular trajectory, and participants were required to press against the force to maintain their index fingers in a steady position. The study revealed a JND of approximately 10%.

Lee and Hannaford [29] asked the participants to discriminate two haptic icons with different alignments using two different finger motions. The icons were placed on a horizontal plane at a distance of $4mm$, and participants were asked to explore them using one of two different finger motions, flexion/extension or abduction/adduction. The PENBASED [16] haptic device was used for interacting with the virtual icons. The PENBASED haptic device is a $2DOF$ device, which is similar to a joystick but does not have handheld stick. Instead, it utilizes an aluminum nub to interface with user's fingertip. The results showed that force perception was not affected by the spatial arrangement of the haptic icons. Finger motion, however, affected force perception: The abduction/addition motion lead to a lower force discrimination threshold of $14.5mN$ as compared to one of $23.9mN$ for the flexion/extension motion.

Discrimination of force magnitudes also depends on the relative directions of the forces. Pongrac et al. [3] asked participants to discriminate pairs of forces applied to the stylus of a PHANToM device. In the reference stimulus, a force was applied in a fixed direction (the reference direction), and in the comparison stimuli, a perturbation force was added to the reference force, in directions 0°, 45°, 90°, 135° or 180° relative to the reference force. Participants were required to keep the stylus steady to sense the forces. The force discrimination threshold depended on the direction of the perturbation vector: For directions 0° or 180°, the JND was approximately 10%, and it was in the range of $20 - 30\%$ for the other directions.

Lee and Hannaford [30] evaluated performance gains for an icon-click task with different force intensities. The PENBASED haptic device was used for interacting with the virtual haptic icons. The task required participants to click a color coded target icon among four distracters. Four force magnitude levels, $0N$, $50N$, $100N$, and $300N$ were tested. The participants were separated into two groups. One group performed the experiment with all icons having haptic feedback. The other groups performed the experiment with only the target icon having haptic feedback. Fitts' Information Processing Rate (FIPR) [23] was computed to measure task performance. The authors observed that, for both groups, FIPR increased as the intensity of force feedback was increased. The group with force on the target icon had a higher FIPR than the group with force on all the icons. No statistical analysis was conducted in this study. But later Dosher and Hannaford [20] conducted a similar experiment, and proved statistically that user performance in the icon-click task increased as the intensity of force feedback increased.

The reported thresholds or JND's of force magnitude were mainly obtained without hand or finger motions. The effect of motion on the perception of force magnitude has not been reported. It is plausible to expect that force discrimination is more accurate when the hand is held steady, as in [7] and [3], than when it is required to be moved. This could be due to a number of factors, including the complexity of resulting force directions, as found in [3], or due to the fact that participants have to divide their attention between attending to the execution of a particular hand movement and attending to the discrimination of force magnitudes. We thus expect that the discrimination thresholds of force magnitude would be lower when hand movement is not required than when hand movement is required. Our study that validated this hypothesis will be discussed in Chapter 6.

2.1.6 Velocity Effects

When hand motion is involved, it is also important to determine if and how hand movement speed affects haptic force perception. Lederman et al. [6] , for example, found that perception of surface roughness was impaired by increasing the speed of relative motions. They asked participants to perceive roughness of real surfaces through a grasped stylus. To sense the roughness, the participants stoke across a surface in three predetermined speeds. A computer generated metronome was used to help control striking speed in a way that the beginning and the end of a pen strike coincided with two successive clicks. Surface roughness was rated numerically by non-zero positive numbers. After perceiving the roughness of a surface, the participants picked a rate to best describe it. The study revealed that speed had significant effects on the perception of surface roughness. Perception of roughness decreased as hand movement speed increased.

Wu et al. [4] found that performance in a force control task also decreased as the velocity of hand motion increased. In their study, participants were asked to apply a constant force to a finger pad, which was mounted on a moving robot. The robot moved from right to left in one of nine speeds $(0, 1, 4, 7, 10, 13, 16, 20$, and $30mm/s)$. When the robot was moving, the participants were required to maintain the magnitude of their finger-tip force as close as possible to the magnitude of a target force. The target-force magnitude was visualized as a stable vertical line surrounded by a shaded target box. The target box covered the region of $\pm 15\%$ of the target force. The participants' force intensity was visualized as a color coded vertical line. The vertical line moved horizontally as the force magnitude changed. The participants were instructed to place and hold the magnitude line inside the target box by adjusting their finger-tip force. The study suggested that the participants' ability to maintain a constant force to a moving robot diminished as the velocity of the robot increased.

Findings of these studies showed the evidence of velocity effect. However, no study reported whether hand movement velocity affected the perception of force magnitude and the perception of force direction. We will address this issue in details in Chapter 5 and Chapter 6.

2.2 Haptic Learning

Haptic learning refers to learning activities via the sense of touch. The advantage of providing haptic feedback is that it can improve the performance of tasks that require certain motor skills [67, 5, 62]. In computer science and engineering, research on haptic learning is focused mainly on utilizing haptic interfaces for assisting motor-skill development and skill transfer. Before we discuss more details, we introduce motor skill and motor skill transfer.

2.2.1 Motor Skill and Skill Transfer

A motor skill is a skill that requires effective utilization of muscle, skeleton joints, and limbs of body. Humans use their motor-skills to complete desired actions that need to be properly coordinated. 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. Motor skills that require small motions with high level of precision and accuracy are called fine motor-skills. Fine motor-skills involve manipulation of small objects and various hand-eye coordination tasks.

Motor skills are normally developed through observation and practice, but motor skills can also be gained by direct transfer from other people. An example of such skill transfer is teaching children to write. The teacher holds the child's hand, and physically guide the hand to show the child 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. Here are some advantages of using haptic interfaces in teaching motor-skills:

1. Students can practice ideal trajectories in the absence of instructors.

2. There is no time limitation: Students can practice as long as they like.

3. There is no location limitation: Students can practice anywhere where haptic interfaces are available. With the support of the high-speed Internet, instructors and students can even be in different geographical locations.

4. An instructor can teach more than one student at a time.

5. The instructor's motor skills can be repeated precisely and infinitely.

In the next section, we review the state-of-the-art in haptic motor-skill training systems and the studies conducted on these systems.

2.2.2 Haptic Motor-Skill Training

During the last decade, researchers have widely explored on how to use haptic devices to improve motor-skill acquisition. Many haptic motor-skill trainers have been developed. 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 trainees during the training. Computer monitors usually serve as visual interfaces, and the most commonly used haptic interfaces are PHANToM series from SensAble Technologies [56]. Audio information may also be used to provide extra support [36, 55]. 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 trainee's hand through a desired trajectory at a pre-defined speed so that the trainee can haptically feel the expert's movements through position and velocity cues. In the passive constraint, the trainee 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 trainee feels as if he /or she is moving along a virtual channel, which keeps the end-effector on the correct path.

Portillo-Rodriguez et al. [43] developed a haptic motor-skill training system, that was designed to help users develop the skills of drawing three primitive shapes, circles, lines, and arches. The users could specify the characteristics of the primitives (e.g. size, orientation, etc.). Reference primitives were displayed visually and haptically. The guiding force was provided by a 2DOF haptic device. During training, the user traced the reference primitive to learn to draw, and the system passively constrained the user's hand movements close to the ideal path.

Henmi and Yoshikawa [24] developed an active playback system to teach Japanese calligraphy. The system required masters' trajectories to be recorded in terms of normal pushing force against a virtual paper as well as horizontal and vertical positions of a brush tip. During training, recorded skills were displayed to students through haptic and visual interfaces. The horizontal position of the brush tip was displayed haptically in an active playback fashion, in which the end-effector of the haptic device was forced to follow the masters' movements at recorded speeds. In the vertical direction, either vertical position or normal pushing force of the brush tip could be displayed haptically. In either case, the rest was displayed visually on a computer monitor. For instance, if the haptic device was dedicated to display the horizontal and vertical positions of the brush tip then both the masters' and the students' normal pushing forces against a virtual paper were visually displayed. The differences between the two forces were visualized as the thickness of the strikes. The system showed some promise but no objective measurements were conducted to demonstrate its effectiveness.

Plimmer et al. [41] proposed the idea of a signature training system, which combined both passive guiding and active guiding. They suggested that the system could dynamically switch from active playback to passive constraint according to the development of a user's skill level. They also suggested that the overall assistance should decrease as the users became more skillful.

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

Williams et al. [65] demonstrated that haptic training is beneficial for hand movement learning. Their virtual placatory diagnosis trainer utilized a PHANToM device 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. The study showed that the trained group performed better than the untrained group.

Avizzano et al. [10] 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 picked from a reference circle were displayed for guiding purpose. With haptic training, a $2DOF$ force feedback device passively constrained participants' hands within the ideal circular trajectory. Results showed that the shapes of the drawn-circles were significantly improved after the haptic training as compared to the visual training.

Tao et al. [53] investigated the skill-transfer ability of a haptically enhanced Chinese learning system, which was developed to teach Chinese pen-writing and brush calligraphy. Two studies were conducted to show the effectiveness of the system, one on pen-writing, and the other on brush calligraphy. In the pen-writing study, character shape and strike smoothness were measured. In the brush calligraphy study, character shape, normal forces against a virtual paper, and pause-and-go motion were measured. 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 [53], Morris et al. [35] 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. When displayed haptically, the normal force was presented in the opposite direction. The participants were asked to beat the force to perceive the magnitude. When displayed visually, two energy bars were used to represent the reference force magnitude and the user-applied force magnitude. When display visuohaptically, both visual and haptic feedbacks were provided. The study 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 and Thenkurussi [49] 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 writing forces were passively displayed by a PHANToM device. Findings confirmed that haptic training was helpful for recalling a series of force information. However, the study also showed that haptic guiding did not promote character-shape learning. In their later research [48], Srimathveeravalli et al. showed that the force pattern was unique across different people when performing the same task. Furthermore, they showed that force pattern remained invariable for a given task performed by the same person.

Similar to [49], Solis et al. [47] did not find haptic training to be beneficial for motor learning. They evaluated the skill-transfer ability of a Japanese character training system [46] under three training methods: visual-alone, haptic-alone, and visuohaptic. Task completion time, overall correction force magnitude, and character shape were evaluated 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. Feygin et al. [21] also found haptic training not helpful for motor skill development. Their study consisted of training participants to learn arbitrary trajectories under three paradigms, haptic-alone, visual-alone, and visuohaptically. Haptic assistance was provided in an active guiding fashion, in which, the participants' hands were forced to move through an ideal trajectory by a haptic device. Training outcomes were evaluated under two post-training paradigms, haptic-alone and visuohaptic. The study revealed that haptic training was effective with respect to the temporal aspect of the task, while motor skill improvements were mainly due to the trainings with visual information.

However, Adams et al. [2] argued that haptic feedback was not helpful for improving task completion time. They studied the influences of visuohaptic training for a manual assembly task. The task was to construct a LEGO biplane. Participants were separated into three groups. One group built the biplane without training. The remaining two groups practiced to build the biplane using a virtual building block simulator prior to the real task. Haptic feedback was provided to only one of the training groups. Training outcomes were assessed in terms of task completion time. The study did not find training with haptic feedback improved temporal aspect of the task in comparison with training without haptic feedback.

In spite of different study results, one common finding reported in the cited literature was that visuohaptic training was the most effective training method for motor skill acquisition. We also noticed that the success of skill transfer was mainly reported immediately after the trainings. For example, in Avizzano et al. [10]'s study, the participants performed the post-training tests immediately after a training session when the just-learned skills were freshly stored in muscle memory. The performance of the post-training tests was subsequently used to demonstrate the success of skill transfer. Same method can be found in [65, 53, 35, 49, 47, 21, 2]. Note that just-gained motor skills can be lost rapidly in absence of haptic assistance after an intensive training phase [33]. 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 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. The associative stage is the stage where people learn how to conduct a motion. Finally, in the autonomous stage, people can master the task. [65, 10, 53, 35, 49, 47, 21, 2] 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 whether haptic training can improve the process of learning by promoting skill transfer from the associative stage to the autonomous stage.

In this thesis, we report two studies that were conducted to investigate the effectiveness of haptic training in motor skill development. The findings of these two studies helped us gain a better understanding of motor skill learning. Details are discussed in Chapter 3 and Chapter 4.

Chapter 3

Short-term Motor-Skill Learning

This study investigated whether haptic training is beneficial for short-term motor-skill development. We compared training outcomes from three training methods, no-assistance training, visual training, and visuohaptic training. Instant skill improvement was measured to determine the most effective training method.

3.1 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.

3.2 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 at a comfortable viewing distance. 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

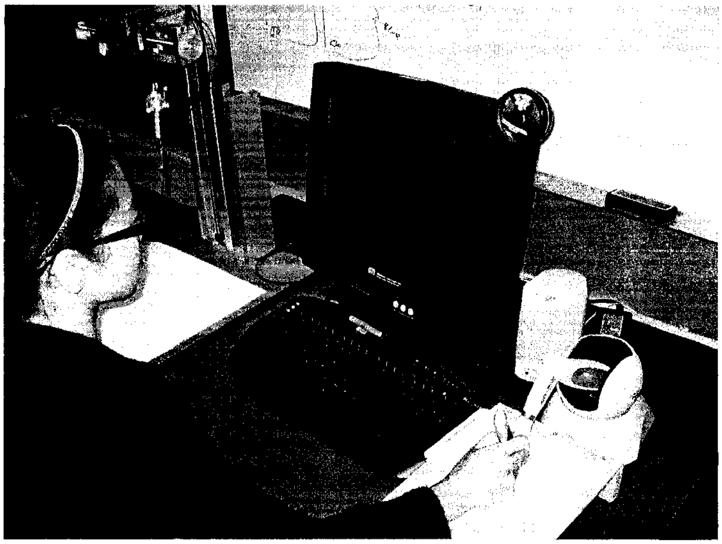

Figure 3.1: Experimental setup for the study on short-term motor-skill learning.

like holding 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 with the non-dominant hand (see Figure 3.1).

The test system was developed in C++ using the Open Haptics toolkit from SensAble Technologies [56] and was run on a dual-CPU $2GHz$ Pentium Dual Core computer with $4G$ RAM running Windows XP.

3.3 Experimental Design

Participants were required to learn three trajectories, triangle, rectangle, and ellipse, with three training methods (see Figure 3.2). The reference trajectories were thus drawn by hand by an "expert" on the horizontal plane. The training was conducted under three paradigms:

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

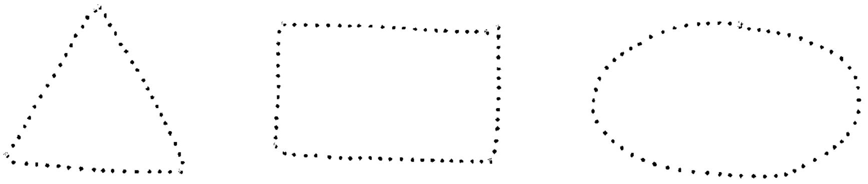

Figure 3.2: The base trajectories for the study on short-term motor-skill learning.

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

$$\begin{array}{ccc} T_1 & T_2 & T_3 \\ T_1 & T_3 & T_2 \\ T_2 & T_1 & T_3 \\ T_2 & T_3 & T_1 \\ T_3 & T_1 & T_2 \\ T_3 & T_2 & T_1 \end{array}$$

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 3.3), on the assumption that changing the orientation of a trajectory does not change its difficulty level for learning. Therefore, 9 trajectories were tested in total.

3.4 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 trajectories as described above, and the end-effector was dragged back to the ideal path.

The direction of the correction force was calculated by projecting the position of the end-effector onto a sub-trajectory. A sub-trajectory is a segment of the reference trajectory that was determined by feature points. The feature points were set where the reference path turned about an angle greater than 45o. 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 in the x, y, and z coordinates. Projecting a sample point from user trajectory onto the reference trajectory can

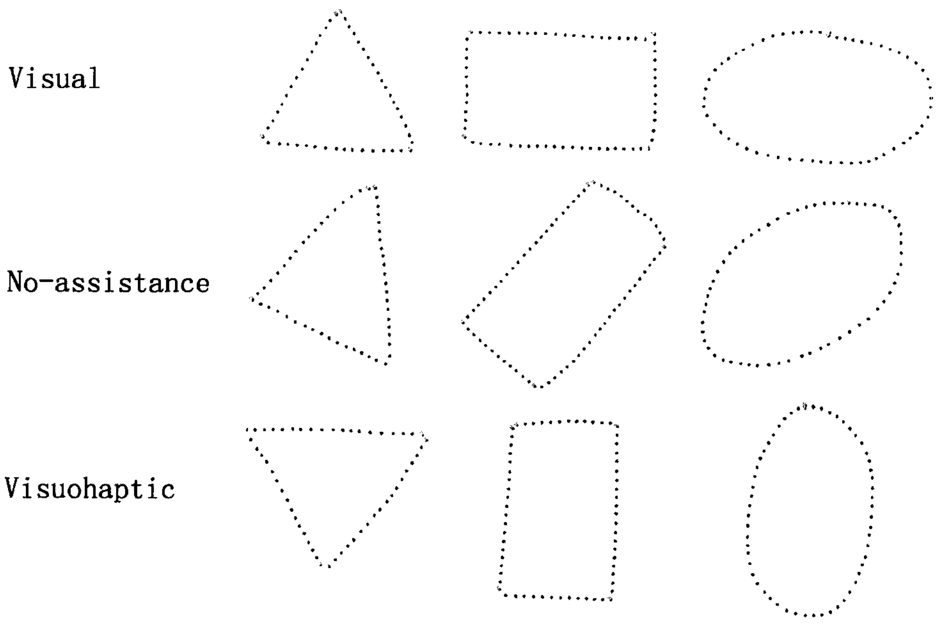

Figure 3.3: An illustration of training order group T_2 T_1 T_3.

therefore be simplified by projecting the sample point onto a line segment connecting two adjacent points from the reference trajectory. 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 $\frac{(w-1)}{2}$ determined the number of line segments to be projected on both sides of p_{last}. In the current study, we chose w to be 11. Therefore, we projected the end-effector only onto the line segments ranging from $p_{last} - \frac{(w-1)}{2}$ to $p_{last} + \frac{(w-1)}{2}$. Note that the range should yield the bounds of the chosen sub-trajectory.

3.5 Visual Feedback

Visual feedback 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 3.4), the reference trajectories were displayed in

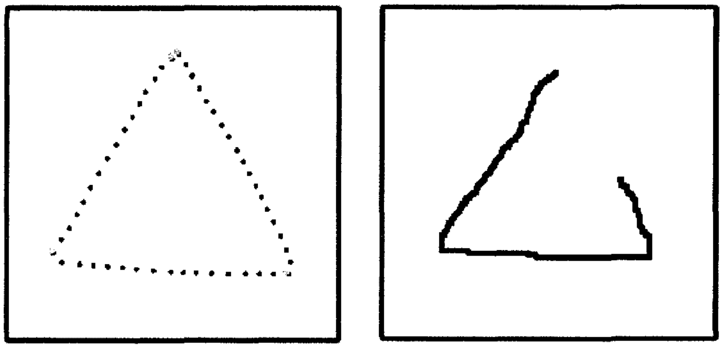

Figure 3.4: An illustration of no-assistance training. The reference trajectory was displayed in the left drawing box, and user trajectories were displayed in the right drawing box.

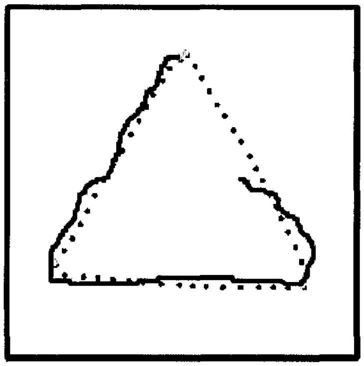

Figure 3.5: An illustration of visual training. Participants traced the reference trajectory to practice.

the left box, and user trajectories were displayed right box. In visual training, the reference trajectory was displayed in the drawing box. Participants learned to draw the trajectory by tracing it in the drawing box (see Figure 3.5). In visuohaptic training, the same visual feedback was provided, but, 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 both, in 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. 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 movement was 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.

3.6 Procedure

Participants practiced in a warm-up session prior to the actual 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 the three 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, $9(blocks) \times 2(speeds) \times 10(repetitions) \times 12(participants) = 2160$ user trajectories were collected for analysis.

3.7 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.

3.8 Results and Discussions

Mean deviations were computed for each recorded trial. A score for a test trial was calculated by averaging the deviations of 10 trials. The lower a participant scored in a trial, the better he /or she performed in that trial. The participant received one score for pre-training test and one score for post-training test for each of the 9 trajectories (see Table 3.1). The scores were analyzed using an analysis of variance (ANOVA) with trajectory shape, training method, and training effect (performances 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

Table 3.1: Mean deviations of pre and post training under the tested training methods 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

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 3.6 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 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 3.7), 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, $t(11) = 3.26,\ p < 0.05$.

For the ellipse trajectory (see Figure 3.8), the participants' skills improved slightly, with all of the three methods. None of the training outcomes was significant, $t(11) = 1.52,\ p >$

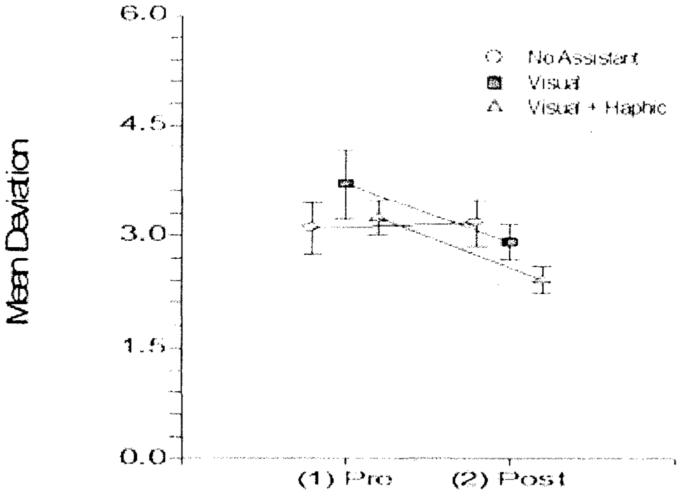

Figure 3.6: Learning curves of the triangle trajectory. Means and standard errors are shown. For clarity, the data points are shifted along the x-axis.

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.

Considering the training outcomes over all the trajectories, the participants' skills were improved after training (see Figure 3.9). More specifically, the participants improved their skills significantly after being trained with visual and haptic assistance, $t(11) = 4.2,\ p < 0.05$. The participants' skills were also improved significantly by the visual training, $t(11) = 4.81,\ p < 0.05$. No-assistance training was not as helpful as the other two training methods, as the user performance did not improve, $t(11) = 1.84,\ p > 0.05$.

The findings suggest that visual training was the most effective training method for short-term motor skill learning in comparison with visuohaptic training and no-assistance training. The findings also indicate that training outcome is depending on the complexity of the motor skill to be learned. For example, the participants made more progress on the rectangle trajectory then the triangle and ellipse trajectory (Figure 3.10).

3.9 Conclusion

Based on the findings, we conclude that visuohaptic training is not as affective as visual training on helping trainees gain short-term motor skills. In the next chapter, we will investigate the performance of haptic training in assisting long-term motor-skill development.

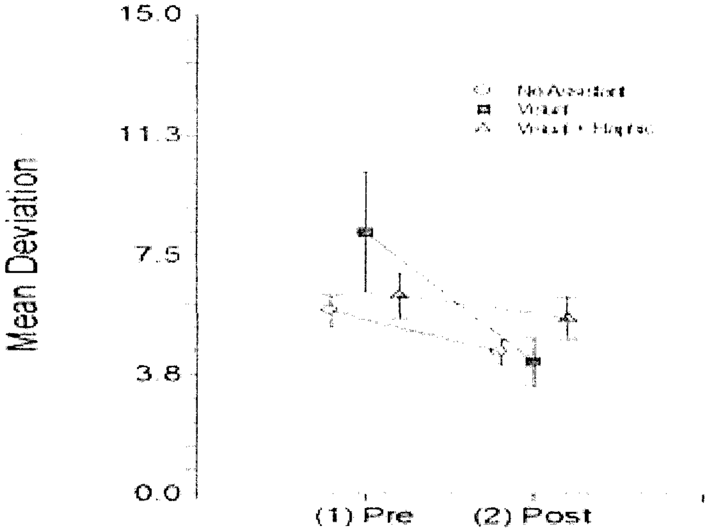

Figure 3.7: Learning curves of the rectangle trajectory. Means and standard errors are shown.

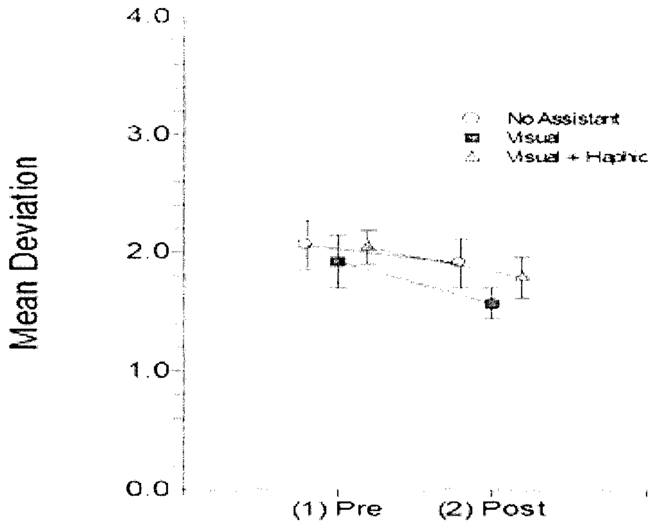

Figure 3.8: Learning curves of the ellipse trajectory. Means and standard errors are shown.

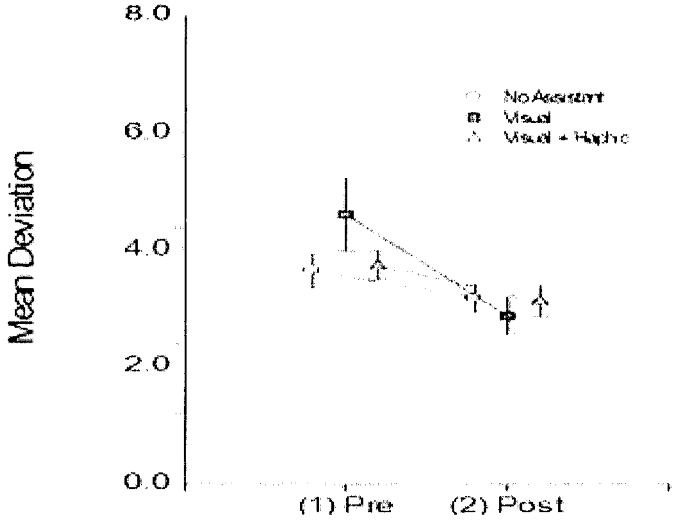

Figure 3.9: Learning curves of training methods. Means and standard errors are shown.

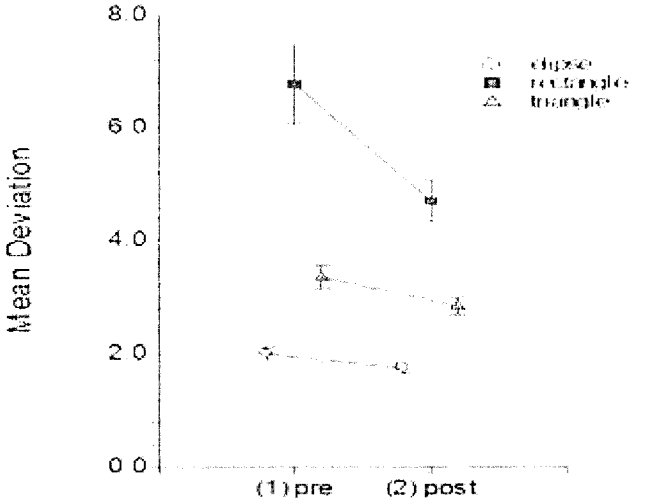

Figure 3.10: Skill-gain curves for the tested trajectories.

Chapter 4

Long-term Motor-Skill Learning

The previous study showed that both visual training and visuohaptic training are beneficial for short-term motor-skill development. However, the study also showed that the participants gained more skills through visual training. In this study, we compared the performance of the two training methods in helping participants gain long-term motor-skills. Skill improvement through a 4-day-long training period was measured to determine the most effective training method for motor-skill learning.

4.1 Participants

Ten participants participated in this study. None of them took part in the the previous experiment. The group consisted of 3 women and 6 men 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 dollars for participation. The participants were informed about the purpose of the experiment, procedure, benefits, possible risks, and their right. 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.

4.2 Apparatus

The apparatus was the same as in the previous experiment

4.3 Experimental Design

Participants were required to learn two complex trajectories (see Figure 4.1), under visuohaptic training and under visual training. We assumed that these two similar yet different

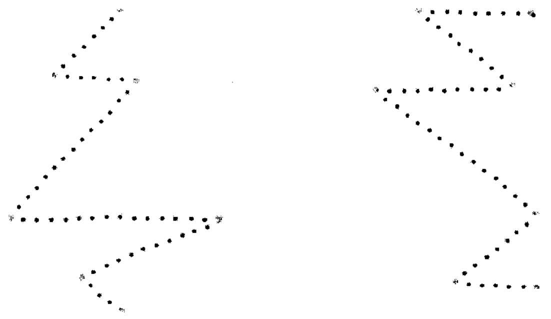

Figure 4.1: The reference trajectories for the study on long-term motor-skill learning.

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" by hand on the horizontal plane. As the no-assistance training has been proven ineffective in the previous experiment, only visual training and visuohaptic training were studied.

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

$$\begin{array}{cc} S_1T_1 & S_2T_2 \\ S_2T_2 & S_1T_1 \\ S_1T_2 & S_2T_1 \\ S_2T_1 & S_1T_2 \end{array}$$

Where T_1 refers to the visual training, T_2 refers to the visuohaptic training, S_1 refers to the left trajectory in Figure 4.1, and S_2 refers to the right one. The participants were randomly assigned to one of the 4 order groups.

4.4 Haptic Feedback

Haptic feedback was the same as in the previous experiment.

4.5 Visual Feedback

Visual feedback was the same as in the previous experiment.

4.6 Procedure

The performance of haptic training in helping people obtain long-term skills was investigated. Therefore, the procedure was similar to the previous experiment except that the participants were learning to draw the trajectories over a period of four 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 training. As in the previous experiment, 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; 4) a post-training phase with 10 trials.

4.7 Data Analysis

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

4.8 Results and Discussions

The test trials for the first four days as well as those collected on day five 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 4.2, and for visual training in Figure 4.3. The learning curves are very similar to each other. They both have a 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' performances 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 of the participants after being trained with visual feedback, $t(9) = 0.08,\ p > 0.05$. Regarding 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 those evidences, we conclude that visuohaptic training was as good as the traditional way of visual training in terms of promoting long-term motor skill development.

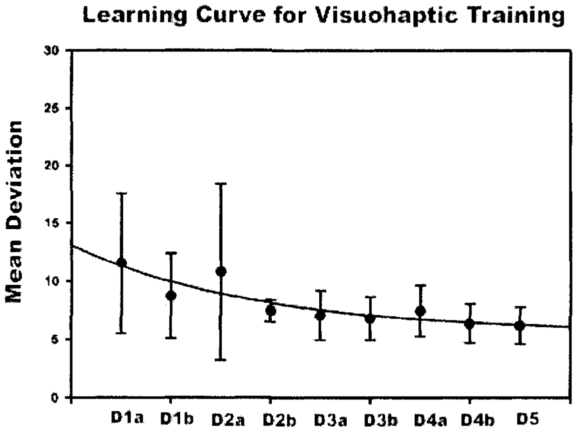

Figure 4.2: Learning curve for visuohaptic training for 5 days in a row. The horizontal variables "Dxa" refers to the pre-training test on day x, and"Dxb" refers to the post-training on day x. Means, standard errors, and exponential fit are shown.

The previous experiment revealed that visual training was the most effective method for helping people gain short-term motor skills. In contrast to our finding, Avizzano et al. [10] 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 [10],

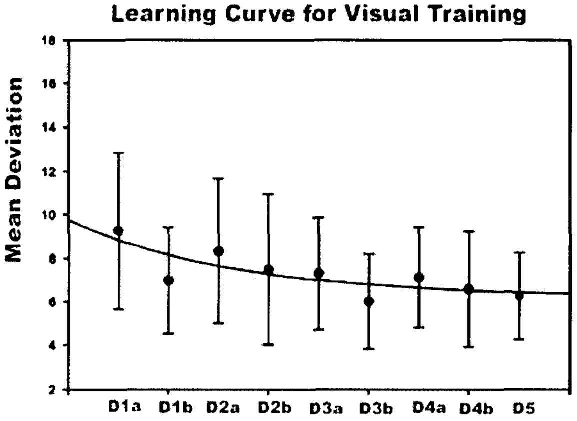

Figure 4.3: Learning curve for visual training for 5 days in a row. The horizontal variables "Dxa" refers to the pre-training test on day x, and "Dxb" refers to the post-training on day x. Means, standard errors and exponential fit are shown.

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 trainees 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 was attractive to many users because of its high-tech background and features such as error correction or expert-skill playback. However, it is actually these features that make the training less helpful. Because the haptic device corrects off-track movements continuously, trainees do not have to correct it by themselves even though they may notice the mistake. Therefore, they tend to follow the guidance passively. As a consequence, they spend less effect in their training, leading to poor outcomes from the training. We believe this is a possible reason that visuohaptic training was less helpful in comparison with 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 feedback showed some promise in this respect in this experiment, 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. There was no significant benefit of using visuohaptic training in terms of skill development. Current visuohaptic training systems could thus be improved or redesigned. 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 trainee is, the more efforts he /or she tends to spend on learning and the better the training outcome will be. Therefore, motivating learning activities and encouraging effort could be a possible directions to explore.

4.9 Conclusion

In the first two experiments, we measured the effectiveness of haptic training with respect to short-term learning and long-term learning. The findings suggest that visual training is the most beneficial for motor-skill development. 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.

Chapter 5

Haptic Perception of Force Direction

Chapter 3 reviewed some recently reported work on the difference thresholds of force direction, which were obtained without hand motions. However, as mentioned, hand motions are usually necessary for most real-world applications. Therefore, we conducted this study to investigate the motion effect on the perception of force direction. In this study, we asked the participants to discriminate different force directions with their hands involving a left-to-right motion, a fundamental component of most hand movements. We also investigated the direction effect when hand movement is involved. Discrimination threshold of force direction for five reference force directions, the same as those in [12] and [52], were measured. To investigate the velocity effect, we tested two different hand movement speeds, slow (14 mm/s) and fast (28 mm/s) with respect to the screen speed.

5.1 Participants

Twenty-five participants from the University of Alberta took part in this study. The group consisted of 3 women and 22 men between the ages of 20 and 35. All of the participants reported a normal sense of touch and vision. Two of them were left-handed, and the rest were all right-handed. The experiment took about 45 minutes, and the participants received $10 dollars for participation. The participants were informed about the purpose of the experiment, procedure, benefits, possible risks, and their right. 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.

5.2 Apparatus

The apparatus was the same as in the previous experiments, except that the plastic sheet was removed from the far end of the armrest since the participants no longer needed to draw on it (see Figure 5.1).

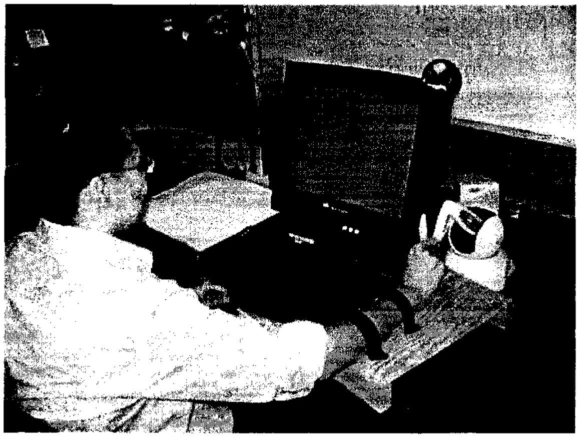

Figure 5.1: Experimental setup for the study on the perception of force direction

5.3 Stimuli

The participants were required to move the stylus at a constant speed from a start position on the left to an end position on the right. During the hand movement, a force was applied to the stylus away from the movement direction with a pre-set angle, and the participants had to detect the direction differences in the forces.

Assuming the hand movement was along the $x\text{-}axis$, the reference force direction was β degree away from the $x\text{-}axis$, where $\beta \in (0^\circ, 45^\circ, 90^\circ, 135^\circ, 180^\circ)$. The reference force directions were the same as those tested in [12] and [52], which allowed us to compare our findings with the reported thresholds.

During the experiment test force deviated from the reference force by an angle α. It could be in any direction, i.e. the phase angle of the test force was chosen randomly in every trial (see Figure 5.2). The force was ramped up from 0 to $1.5N$ within 1s of the trial start and ramped down to 0 within $1s$ of the trial end (see Figure 5.3).

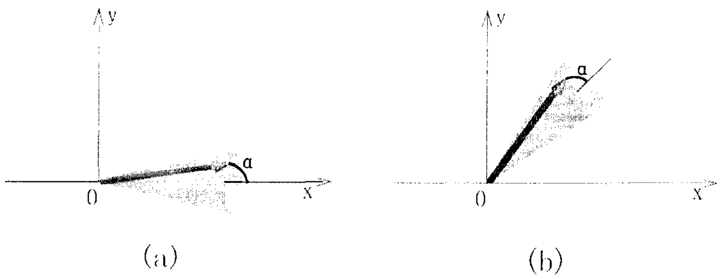

Figure 5.2: The test force vector could point in any direction, as long as the angle between which and the $x\text{-}axis$ was equal to α. For instance, if the reference force direction was 0° then the test force could lie anywhere on the cone in (a) and if the reference force direction was 45° then the test force could lie anywhere on the cone in (b).

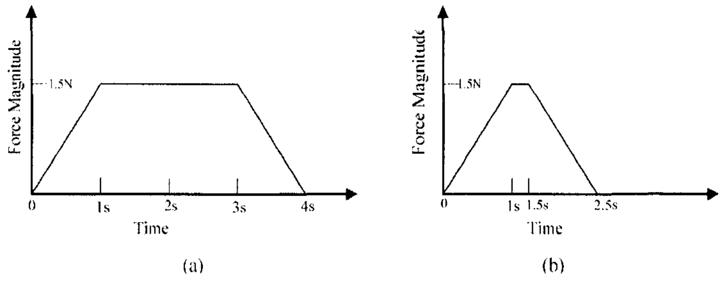

Figure 5.3: Illustration of the temporal force magnitude curves for slow motion (a) and fast motion (b).

5.4 Visual Feedback on Hand Movement

The task was to move the stylus horizontally from a start position to an end position to form a left-to-right motion. The start and end position were graphically displayed by yellow 3D spheres of $1mm$ diameter and a distance of $42mm$. The stylus position in the $3D$ space was represented by a blue spherical cursor (the dark sphere in Figure 5.4b). To prevent participants from moving off the straight trajectory, we put a virtual cylinder between the start point and the end point. The cylinder was $23mm$ in diameter. It was made semi-visible so that the participants could see the cursor moving in it. The participants were instructed to move the cursor from the cylinder's left end to its right end without touching the cylinder. Depth information is lost on a 2D display, but it was particularly important to our participants because they used it to avoid touching the front and back side of the cylinder when adjusting the cursor position. We thus also rendered a side view representation of the cylinder (the circle in Figure 5.4a) and the cursor.

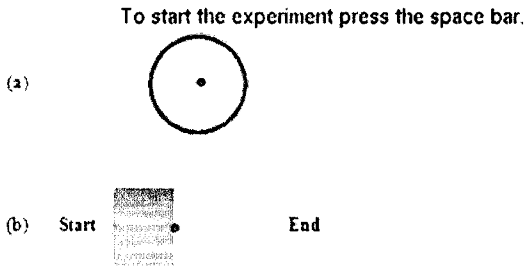
To start the experiment press the space bar.

Figure 5.4: The screenshot of the visual feedback. (a) The side view of the virtual cylinder and the main cursor. (b) The normal view, in which, the gray area between the start position and the main cursor is the progress bar.

To facilitate the velocity control, we used a progress bar (see Figure 5.5). The red speed bar had the same height as the cylinder. It started from the start position and progressed to the right at the desired speed until it crossed the end position. Participants were asked to follow the speed bar while moving the main cursor in order to meet the speed requirement. There were two speed levels, slow (14 mm/s) and fast (28 mm/s). It took 3s for the speed bar to progress across the cylinder in the slow-speed condition, while it took 1.5s in the fast-speed condition. We used another progress bar to show the horizontal position of the main cursor (see the gray area in Figure 5.4b). This progress bar was similar to the speed bar except that its right end followed main cursor's horizontal position. The blue progress bar was made semi-transparent so that the participants could always see the speed bar. To move at a desired speed, the participants needed to place and maintain the right end of the progress bar as close as possible to the right end of the speed bar.

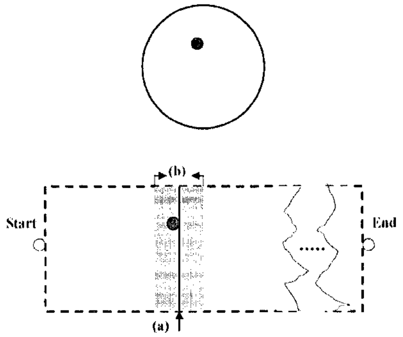

Figure 5.5: This sketch shows (a) the right end of the speed bar and (b) the tolerance region of the speed bar. The dashed lines indicate the virtual tube.

Given that it is difficult to move at precise speed, we created a tolerance region for the speed bar. It was 1mm wide on each side of the right end of the speed bar. It worked in a way that we considered it to be the desired speed as long as the right end of the progress bar was maintained inside the tolerance region. In such case, the cursors were painted yellow to indicate a "following" status. Whenever the participant did not follow the speed bar, the cursors turned to red to indicate a "not following" status. In addition, we created another tolerance region for the start position (Figure 5.6). It was 2mm wide to the right of the start position. The participants could place the main cursor anywhere within the tolerance region to start a trial. As long as the main cursor was placed in the tolerance region of the start position, the progress bar and the cursors were painted by yellow to indicate a "good-to-go" status.

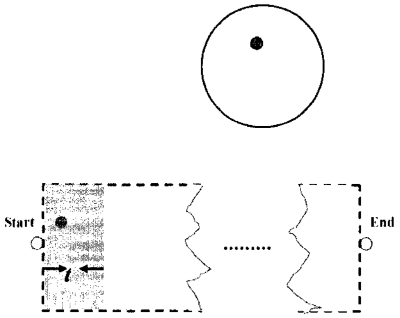

Figure 5.6: The gray area t indicates the tolerance region of the start position. The dashed lines indicate the virtual tube.

With this visual feedback, it is possible to discriminate the force directions by comparing the cursor trajectories. Therefore we hid the cursor and its side view representation after a trial started. The cursors were only displayed before the trials so that the participants could adjust the position of the cursors to place them in the middle of the cylinder. A good start position helped the participants to avoid touching the cylinder while moving the cursor in it.

5.5 Procedure

The participants practiced warm-up trials before the actual experiment to ensure that they were able to master the moving task so that they could attend to the task of discriminating force magnitudes. The participants were asked to practice as much as they wanted until they could master the task. The warm-up sessions took between 5 and 20 minutes.

The task required the participants to discriminate force directions while moving the main cursor from the tube's left end to its right end in a desired speed without touching the tube wall. Before starting a trial, the participant placed the main cursor in the tolerance region of the start position, where s/he could see the progress bar and the cursors turned to yellow to indicate a "good-to-go" status. The participant was also asked to adjust the cursors' positions by placing them in the middle of the tube. This ensured a good starting position to avoid touching the tube while moving. After a trial was started, the participant moved the progress bar to follow the speed bar by placing the right end of the progress bar in the tolerance region of the speed bar.

An experiment consisted of a number of blocks, and each block consisted of three trials, two with the reference force (β) and one with the test force ($\beta + \alpha$). In each trial, the current stimulus numbers (1, 2, or 3) and the desired hand movement speed were clearly displayed on the computer monitor. The three trials within a block were randomly ordered, and participants had to indicate which of the three trials had a different force magnitude by entering 1, 2, or 3 on the keyboard. Responses were recorded and used to determine the value of α in the next block. For each trial, the participant's hand movement was analyzed for validity. If he /or she followed the speed bar at least 90% of the time then his /or her their hand movement was considered as a good trial, and the next trial was presented. If not, the whole block was restarted.

The discrimination threshold of haptic force direction was found using a one-up-two-down adaptive staircase method [31], which tracks a level of 70.7% correct responses. The test force deviation $\delta\alpha$ was set to 9°, the step size α was initially set to 9°, and α was increased by $\delta\alpha$ after each incorrect response and decreased by $\delta\alpha$ after 2 consecutive correct responses. After 5 staircase reversals, $\delta\alpha$ was set to 2°. A staircase run was terminated after 10 reversals with $\delta\alpha = 2°$. The experiment finished after two staircase runs were completed.

The participants were not given feedback about the correctness of their responses in either the warm-up blocks or the experimental blocks.

5.6 Experimental Design

Participants were divided into five groups. Each group tested one of the force directions at two levels of hand movement speed, slow and fast. The force directions were randomly assigned to the groups, and the speed levels were fully counter-balanced.

5.7 Results

The averages from the last 10 staircase reversals were calculated for each participant. Each participant's discrimination threshold was then calculated by averaging these averages. The estimated discrimination threshold of haptic force direction for each force direction was computed by averaging the thresholds of the corresponding group (Table 5.1). The estimated thresholds were analyzed using a two-way mixed analysis of variance (ANOVA) with force direction as a between-subjects factor and (hand-movement) speed as a within-subjects factor.

The ANOVA reported there was no significant effect of the reference direction, $F(4,40) = 1.13$, $p > 0.05$. There was also no significant effect of hand-movement speed, $F(1,40) = 0.23$, $p > 0.05$, and no interaction between force direction and hand movement speed, $F(4,40) = 0.47$, $p > 0.05$.

Table 5.1: Average thresholds of force direction as a function of hand movement speed and force direction

	Force Direction					
Speed:	0°	45°	90°	135°	180°	Average
Fast	24°	43°	29°	39°	29°	33°
Slow	28°	33°	29°	31°	32°	31°
Average	26°	38°	29°	35°	30°	32°

5.8 Discussions

Our study revealed an average difference threshold of force direction of 32° (see Table 5.1), which suggested that in the situations where the change of force direction is less than 32°, additional visual cues may be needed to facilitate awareness. For instance, assume a motor skill training system leads a user's hand through an expert's trajectory from position A to position C (Figure 5.7). The trajectory turns about α degree at position B. Based on the threshold we have found, if α is less than 32°, the user will not be aware of the direction change and will likely continue moving towards position D. Therefore, visual clues should be provided to avoid mistakes.

The threshold found in the present study can also be helpful for optimizing the communication channel of haptic collaborative systems [14, 27, 40]. In such systems, the haptic devices are physically connected by network, and haptic signals are transferred under certain bandwidth. Our findings suggest that any force-direction changes, which are less than

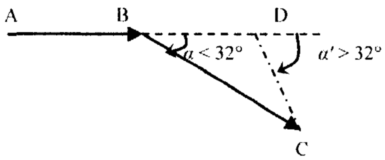

Figure 5.7: If the change of haptic force direction is less than 32°, the user will not be able to follow the ideal trajectory of ABC. Instead, the user will likely follow a wrong trajectory of ABD.

32° are normally undetectable. Therefore, such changes can be discarded from communication packages to save network bandwidth.

To investigate the motion effect, we compared our findings with the thresholds reported in the literature where no hand motion was involved. Tan et al. [52] stated that the discrimination thresholds of force direction ranged from 25° to 33°. This range was found on the participants' steady index fingers. Our discrimination threshold of force direction was found by measuring force-direction changes when moving a stylus. We found that the threshold was 32°, which appeared to be within the reported range. To prove statistically, a one-sample $t - test$ was conducted to compare our finding, $M = 32°$, $N = 50$, against the lower and upper bound of the reported threshold range. [1]. The results show that 32° is significantly higher than the lower bound 25°, $t(49) = 3.2437$, $p < 0.001$, and statistically similar to the upper bound 33°, $t(49) = -0.7193$, $p > 0.05$. Therefore, we conclude that the perception of force direction is not affected by the left-to-right hand motion. Our conclusions cannot go beyond this conclusion because the direction of hand movement may possibly affect the perception of force direction. More work is required to determine the motion effect.

As mentioned, it is important to determine if and how hand movement speed affects haptic force perception. The ANOVA analysis revealed that the speed of hand movement did not affect the perception of force direction. Figure 5.8 shows that the threshold curves of were similar for fast motion versus and slow motion. However, people normally explore the virtual world within a range of hand-movement speeds. Within that range, people appear to be able to precisely perceive the virtual world haptically without being affected by hand movement speed. However, if hand movement speed exceeds the upper speed boundary, haptic perception should be impaired. This may be attributed to the velocity effect or due to

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[1] The one-sample $t - test$ compares the mean score of a sample to a known value. The known value is a population mean.

reduced duration of haptic stimulation. To the best of our knowledge, such speed limit has not been reported. We chose the speed levels based on our observation of the speeds with which people usually move their hands to perceive the virtual world. Thus the tested speed levels were falling into a range of practical importance. Therefore, we suggest that hand movement speed does not affect human perception of force direction when it falls into this range. The velocity effect may appear when hand movement speed approach or exceed the speed limit.

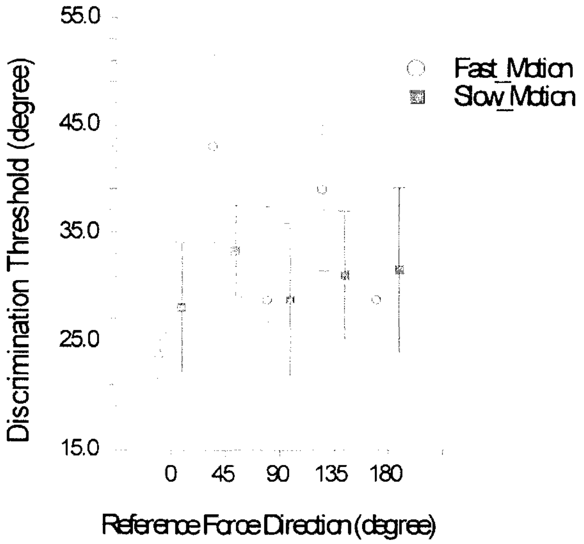

Figure 5.8: Discrimination thresholds of force direction for five reference force directions at two speed levels. Means and standard errors are shown.

Regarding the direction effect, the perception of force direction was found to be independent of reference force direction. This result is consistent with the finding reported in [52], and it thus indicates that the perception of force direction is not impaired by the oblique effect [9]. However, as previously mentioned, the tested speed levels were falling into a range of practical importance. The direction effect and/or the oblique effect may appear to impair the perception of force direction if the speed of hand movement exceeds the upper bound of the range. Hence, we suggest that the reference force direction does not affect the perception of force direction when hand movement speed falls into this range.

5.9 Conclusion

The findings of the this study show a preliminary picture of the relationship between perception of force direction and hand motion. We found the discrimination threshold of haptic force direction to be 32°. We also found that hand-movement speed and reference-force direction did not affect the perception of force direction. However, we do not yet know how fast humans can move their hands and still be able to perceive force direction precisely. The tested speed levels were assumed to be within the range of practical importance. Therefore, our findings should be considered true under limited conditions. A velocity effect or direction effect may appear when the speed of hand movement approaches or exceeds the speed limit.

Chapter 6

Haptic Perception of Force Magnitude

We conducted this study is to validate our hypothesis of motion effects on the perception of force magnitude, which states that the discrimination thresholds of force magnitude is lower when hand movement is not required than when the hand movement is required. Therefore, we asked the participants to discriminate different force magnitudes with their hands involved in a left-to-right motion. We also tested two different hand movement speeds, slow (14 mm/s) and fast (28 mm/s), to investigate the velocity effect. Furthermore, we noticed that most of the existing haptic motor skill training systems either actively lead the trainee's hand through an ideal trajectory or passively constrain the trainee's hand movements within the ideal trajectory. In either case, the guiding force changes its direction continuously. Hence we were also interested in how human perception of force magnitude changes with the changes in force direction, and we tested five different force directions, $0°$, $45°$, $90°$, $135°$, and $180°$ relative to the hand movement direction. For each direction, we obtained an average force discrimination threshold to determine a direction effect in the perception of force magnitude.

6.1 Participants

Twenty five participants took part in this study. The group consisted of 3 women and 22 men between the ages of 20 and 30. All of the participants reported a normal sense of touch and vision. Two of the participants were left-handed, and the rest were all right-handed. The experiment took about 45 minutes, and the participants received $10 dollars for their participation. The participants were informed about the purpose of the experiment, procedure, benefits, possible risks, and their rights. Every participant signed a consent form prior to performing the experiment.

6.2 Apparatus

The apparatus was the same as in the last experiment of Chapter 5.

6.3 Stimuli

Participants were required to move their hand at constant velocity from a starting point on the left to an end point on the right. During the hand movement, a force was applied to the stylus away from the movement direction, and participants had to detect magnitude differences in these forces. In the following, we first describe the forces that were applied, and then we describe the visual feedback that was given to control the hand movement.

Assuming the hand movement was along the x-axis, the force direction was either 0°, 45°, 90°, 135°, and 180° away from the x-$axis$, and on the cone defined by the x-$axis$ and the direction angle. The force could be in any direction, i.e. the phase angle of the force was chosen randomly in every trial (see Figure **??**). For reference trials, the magnitude S of the force was $1.5N$, and for test trials, the force magnitude was $S \pm \delta S$, where δS is a positive number representing the difference between the reference and test force. The value of δS was determined adaptively, as described below. The test force could thus be greater or smaller than the reference force.

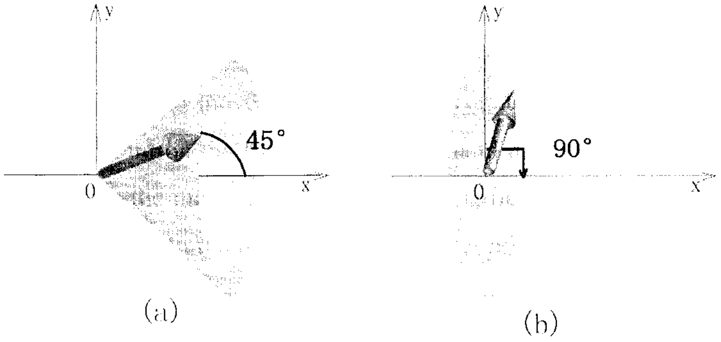

Figure 6.1: The force vector could point in any direction, as long as the angle between which and the x-axis was equal to one of the force directions (0°, 45°, 90°, 135°, and 180°). For instance, if the force direction was 45° then the force could lie anywhere on the cone in (a) and if the force direction was 90° then the force could lie anywhere on the disc in (b).

The force was ramped up from 0 to the target value (either reference magnitude or test magnitude) within 1s of the trial start and ramped down to 0 within 0.5s of the end of the trial (see Figure 6.2).

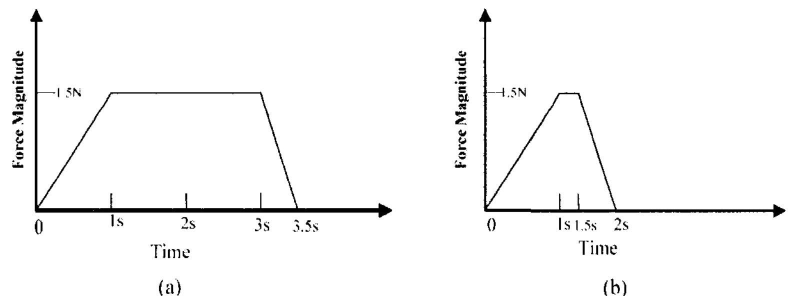

Figure 6.2: Illustration of the temporal force magnitude curves for slow motion (a) and fast motion (b).

6.4 Visual Feedback on Hand Movement

Visual feedback was mainly the same as in the last experiment except that the side views were displayed during a trial. This is because force magnitudes are unlikely to be discriminated by visual clues.

6.5 Procedure

The participants performed warm-up trials before the actual experiment to ensure that they were able to master the moving task so that they could attend to the task of discriminating force magnitudes. The participants were asked to practice as much as they wanted until they could master the task. The warm-up sessions took between 5 and 20 minutes.

The task required the participants to discriminate force magnitudes while moving the main cursor from the cylinder's left end to the right end at a desired speed, without touching the cylinder. Before starting a trial, the participant placed the main cursor in the tolerance region of the start position, where he /or she could see the progress bar and the cursors turned to yellow to indicate a "good-to-go" status. The participant was also asked to adjust the cursors' positions by placing them in the middle of the cylinder. This ensured a good starting position to avoid touching the tube wall while moving. After a trial was started, the participant moved the progress bar to follow the speed bar by placing the right end of the progress bar in the tolerance region of the speed bar.

An experiment consisted of a number of blocks, and each block consisted of three trials, two with the reference force (S) and one with the test force ($S \pm \delta S$). In each trial the current stimulus numbers (1, 2, or 3) and the desired hand movement speed were clearly displayed on the computer monitor. The three trials within a block were randomly ordered, and participants had to indicate which of the three trials had a different force magnitude by entering 1, 2, or 3 on the keyboard. Responses were recorded and used to determine the value of δS in the next block. For each trial, the participant's hand movement was analyzed for validity. If s/he followed the speed bar at least 90% of the time then his/her their hand movement was considered as a good trial, and the next trial was presented. If not, the whole block was restarted.

The discrimination threshold of haptic force magnitude was found using a one-up-two-down adaptive staircase method [31], which tracks a level of 70.7% correct responses. The force magnitude S was set to $1.5N$, the step size δS was initially set to $0.2N$, and it was increased by $0.2N$ after each incorrect response and decreased by $0.2N$ after 2 consecutive correct responses. After 5 reversals, δS was set to $0.02N$. A staircase run was terminated after 10 reversals with δS = 0.02N. In other words, there were 15 reversals in each staircase run. The experiment finished after two staircase runs were completed.

The participants were not given feedback about the correctness of their responses in either the warm-up blocks or the experimental blocks.

6.6 Experimental Design

Participants were divided into five groups. Each group tested one of the force directions at two levels of hand movement speed, slow and fast. The force directions were randomly assigned to the groups, and the speed levels were fully counter-balanced

6.7 Results

One participant was not able to finish the experiment. So data from 24 participants were analyzed. The average from the last 10 reversals were calculated for each participant. Each participant's discrimination threshold was then calculated by averaging these means. The estimated discrimination threshold of haptic force magnitude for each force direction was computed by averaging the thresholds of the corresponding group (Table 6.1). The estimated thresholds were analyzed using a two-way mixed analysis of variance (ANOVA) with force direction as a between-subjects factor and (hand-movement) speed as a within-subjects factor.

The ANOVA analysis concluded that there was a significant effect of force direction, $F(4, 38) = 6.91$, $p < 0.001$; means are shown in Table 6.1. There was no effect of hand-movement speed, $F(1, 38) = 0.25$, $p > 0.05$; and no interaction between force direction and hand movement speed, $F(4, 38) = 0.43$, $p > 0.05$. Tukey-Kramer tests showed that the discrimination threshold found for 45° with fast motion was different from the discrimination thresholds found for 0° with both, fast and slow motion.

Table 6.1: Average thresholds and JND's as a function of hand movement speed and force direction.

	Force Direction					
Speed:	0°	45°	90°	135°	180°	Average
Fast	$0.49N$ 33%	$1.01N$ 67%	$0.84N$ 56%	$0.6N$ 40%	$0.51N$ 34%	$0.69N$ 46%
Slow	$0.44N$ 29%	$0.83N$ 55%	$0.8N$ 53%	$0.69N$ 46%	$0.52N$ 35%	$0.66N$ 44%
Average	$0.47N$ 31%	$0.92N$ 61%	$0.82N$ 54.5%	$0.65N$ 43%	$0.52N$ 34.5%	$0.68N$ 45%

6.8 Discussions

The relatively high force discrimination thresholds found in this study indicate that the perception of force magnitude is impaired when the hand is moving, as opposed to conditions when the hand remains static (see [7] and [3]). The results also suggest that, in systems where haptic force magnitude needs to be changed frequently, the magnitude of haptic force change may need to be as high as 67% of the original force in order for people to detect a difference. This implies that some of the low-end haptic devices in the current market may not be suitable for the tasks requiring dynamic force magnitude changes because they may not produce force magnitude sufficiently high of haptic interactions.

As mentioned in the first section, we hypothesized that the discrimination thresholds of force magnitude are lower when no hand movement is required than when hand movements are required. To confirm this hypothesis, we compared our findings with the threshold reported in the literature where no hand motion was involved. The discrimination thresholds reported in the literatures are approximately 10% [7, 3], they were found on the participants' steady index fingers or on a steady stylus. Our discrimination thresholds were found by measuring force magnitude changes when moving a stylus. The discrimination threshold reported in the literature were found only for 0° and 180°, so only the 0° thresholds (31%)

and 180° thresholds (35%) were used for the test. A one-sample $t\text{-}test$ was conducted to compare our finding, $JND = 33\%$, $N = 18$ against the reported 10%. The results show that 33% is significantly higher than the reported one, $t(17) = 7.508$, $p < 0.001$. We conclude that human perception of force magnitude is impaired by hand motion.

A statistical analysis of the experimental data showed that the speed of hand movement did not affect the perception of force magnitude. Figure 6.3 shows that the threshold curves of were similar for fast motion versus and slow motion. However, we believe people normally explore virtual worlds within a range of hand movement speeds. The upper bound of the range refers to the speed limit that people normally do not exceed. Within that range, people appear to be able to precisely perceive the virtual world haptically without being affected by hand movement speed. However, if hand movement speed exceeds the upper speed boundary, haptic perception should be impaired. This may be attributed to the velocity effect or due to reduced duration of haptic stimulation. To the best of our knowledge, such speed limit has not been reported. We chose the speed levels based on our observation of the speeds with which people usually move their hands to perceive the virtual world. Thus the tested speed levels were falling into a range of practical importance. Therefore, we suggest that hand movement speed does not affect human perception of force magnitude when it falls into this range. The velocity effect may appear when hand movement speed approach or exceed the speed limit.

Regarding the direction effect, the perception of force magnitude was found to be affected by force direction. More precisely, the discrimination threshold for 45° direction and fast movement (Average Threshold = $1.01N$, $JND = 67\%$) was different from the one for 0° direction and fast movement (Mean Threshold = $0.49N$, $JND = 33\%$) and for 0° direction and slow movement (Mean Threshold = $0.44N$, $JND = 29\%$). Among all the groups, the group with 45° orientation and fast movement has the highest discrimination threshold and the one with 0° orientation and slow movement had the lowest discrimination threshold. This shows that humans perform very differently for these force directions. Pongrac et al. [3] found effects of force direction similar to those reported here. They also found 45° had the highest discrimination threshold. Based on these findings, we suggest that the 45° direction is a weak point for humans to perceive force magnitude. Our conclusions cannot go beyond this, as we did not find differences between 45° direction and the other directions (90°, 135°, and 180°). More work is required to find an adequate explanation for this phenomenon

There is some evidence showing human perception to be impaired in oblique directions

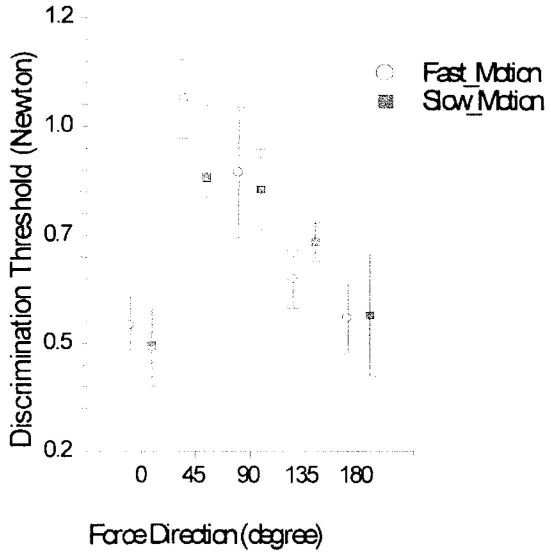

Figure 6.3: Discrimination thresholds of force magnitude at two speed levels upon five force directions. Average and standard errors are shown.

(45° and 135°) [9]. This impairment is called oblique effect. Given that human perception of haptic force magnitude is impaired for the 45° direction, we believe that the oblique effect affect the perception of force magnitude. However, in contrast to the 45° direction, our study does not reveal impairment for the 135° direction. Since the present study only tested the left-to-right motion, we do not know whether the oblique effect exists only at 45°, or whether it depends on the direction of hand movement.

6.9 Conclusion

In this study, we measured the discrimination thresholds of haptic force magnitude. The results showed that humans have a relatively poor sensitivity to force magnitude. The perception of force magnitude can be strongly impaired by hand motions. We also found that hand movement speed did not affect the perception of force magnitude. However, this result was only found with hand movement speeds in a practical range. Our studies of the direction effect suggest that the perception of force magnitude depends on force direction. In particular, people have poorer perception at 45° direction. This indicates the existence of an oblique effect.

Chapter 7

Future Work

This thesis reports the experimental studies of haptic learning and haptic perception. In the first two experiments, we measured the effectiveness of haptic training with respect to short-term learning and long-term learning. The findings suggest that visual training is the most beneficial for motor-skill development. 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.

The findings of the third experiment demonstrate that hand movement speed and reference force direction did not affect the perception of force direction. We also found the discrimination threshold of haptic force direction during hand movement was 32°. However, we suggest that our findings should be considered true under limited conditions, as the tested speed levels were assumed to be within the range of practical importance. We believe that velocity effect or direction effect may appear when the speed of hand movement approaches or exceeds the speed limit.

The results of the last experiment also suggest that hand movement speed did not affect the perception of force magnitude. However, unlike the previous experiment, the study showed that the perception of force magnitude can be strongly impaired by hand motion and force direction. In particular, people have poorer perception at 45° direction. In addition, this result was also found with hand movement speeds in a practical range.

Our findings in the perception of force direction and force magnitude contribute to the perceptive research by taking into account the effects of hand movement and the effects of hand-movement velocity. Haptic perception (active touch) requires active exploration of object characteristics. Hence, hand motion is a critical component. Although, a large number of researches have been conducted to investigate the perception of haptic force, none was conducted with hand motion involved. Our findings help us understand whether and how hand motion affects the perception of force direction and force magnitude. In addition, hand motions are normally required for real-world applications, including haptic motor-skill training systems. Therefore, the thresholds found in our studies are more suitable for guiding the design of haptic motor-skill training system and haptic interfaces, as compared to the reported ones found with no hand motion involved. The studies in haptic learning demonstrate the effectiveness of haptic training in both short-term learning and long-term learning. Based on those findings, we conclude that the existing haptic motor-skill training systems needed to be optimized in order to improve their performance. The findings in Chapter 5 and 6 are extremely helpful for the task. Future work will focus on applying those findings to optimize the design of haptic motor-skill training systems to help users to achieve better training outcomes. In addition, experiments will be designed to confirm and identify the speed range. Based on the speed range, velocity effect and direction effect will be further investigated. We also plan to study if and how hand movement direction effects the perception of haptic force direction. Regarding the perception of haptic force magnitude, we will conduct more experiments to find proper explanations of direction effects. Also, more studies are planned to confirm the oblique effect.

Bibliography

[1] P. Abolmaesumi, K. Hashtrudi-Zaad, D. Thompson, and A. Tahmasebi. A haptic-based system for medical image examination. In *Proceedings of IEEE International Conference of Engineering in Medicine and Biology Society (IEMBS)*, pages 1853–1856, 2004.

[2] R. J. Adams, D. Klowden, and B. Hannaford. Virtual training for a manual assembly task. *Haptics-e*, 2(2), 2001.

[3] H. Pongrac adn B. Farber, P. Hinterseer, J. Kammerl, and E. Steinbach. Limitations of human 3d force discrimination. In *Proceedings of Human-Centered Robotics Systems*, 2006.

[4] M. Wu adn J. J. Abbott and A. M. Okamura. Effects of velocity on human force control. In *Proceedings of First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 05*, pages 73–79, 2005.

[5] F. Huang adn R. B. Gillespie and A. Kuo. Haptic feedback improves manual excitation of a sprung mass. In *Proceedings of International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 200–207, 2004.

[6] S. J. Lederman adn R. L. Klatzky, C. L. Hamilton, and G. I. Ramsay. Perceiving roughness via a rigid probe: Psychophysical effects of exploration speed and mode of touch. *Haptics-e*, 1(1), 1999.

[7] S. Allin adn Y. Matsuoka and R. Klatzky. Measuring just noticeable differences for haptic force feedback: implications for rehabilitation. In *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 299–302, 2002.

[8] A. Alamri, R. Iglesias, R. Iglesias, A. E. Saddik, S. Shirmohammadi, and E. Lemaire. Haptic exercises for measuring improvement of post-stroke rehabilitation patients. In *Proceedings of International Workshop on Medical Measurement and Applications*, 2000.

[9] M. L. K. Astrid and J. K. Jan. Haptic perception of spatial relationsh. *Perception*, 28(6):781–795, 1999.

[10] C. A. Avizzano, S. Alvaro, A. Frisoli, and M. Bergmasco. Motor learning skill experiments using haptic interface capabilities. In *Proceedings of IEEE International Workshop on Robot and Human Interactive Communication (ROMAN)*, 2002.

[11] C. H. Bailey and E. R. Kandel. Molecular and structural mechanisms underlying long-term memory. *The cognitive neurosciences*, pages 19–36, 1995.

[12] F. Barbagli, K. Salisbury, C. Ho, C. Spence, and H. Z. Tan. Haptic discrimination of force direction and the influence of visual information. *ACM Transactions on Applied Perception (TAP)*, 3(2):125–135, 2006.

[13] R. F. Boian, J. E. Deutsch, C. S. Lee, G. C. Burdea, , and J.Lewis. Haptic effects for virtual reality-based post-stroke rehabilitation. In *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 247–253, 2003.

[14] P. Boulanger, G. Wu, W. F. Bischof, and X. D. Yang. Hapto-audio-visual environments for collaborative training of ophthalmic surgery over optical network. In *Proceedings of IEEE International Workshop on Haptic Audio Visual Environments and their Applications (HAVE)*, 2006.

[15] J. Broeren, M. Rydmark, and K. S. Sunnerhagen. Virtual reality and haptics as a training device for movement rehabilitation after stroke: a single-case study. *Archives of physical medicine and rehabilitation*, 85(8):1247–1250, 2004.

[16] P. Buttolo and B. Hannaford. Pen based force display for precision manipulation of virtual environment. In *Proceedings of VRAIS*, pages 217–225, 1995.

[17] S. Cholewiak and H. Z. Tan. Frequency analysis of the detectability of virtual haptic gratings. In *Proceedings of Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems.World Haptics*, pages 27–32, 2007.

[18] J. Deutsch, J. Latonio, G. Burdea, and R. Boian. Rehabilitation of musculoskeletal injuries using the rutgers ankle haptic interface three case reports. In *Proceedings of Eurohaptics*, pages 11–16, 2001.

[19] J. DeZazzo and T. Tully. Dissection of memory formation: from behavioral pharmacology to molecular genetics. *Trends in Neurosciences*, 18:212–218, 1995.

[20] J. Dosher and B. Hannaford. Human interaction with small haptic effects. *Teleoperators and Virtual Environments*, 4(3):329–344, 2005.

[21] D. Feygin, M. Keehnder, and F. Tendick. Haptic guidance: Experimental evaluation of a haptic training method for a perceptual motor skill. In *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 40–47, 2002.

[22] P. Fitts and M. Posner. *Human Performance*. Belmont, CA: Brooks/Cole, 1967.

[23] P. M. Fitts. The information capacity of the human motor system in controlling the amplitude of movement. *Experimental Psychology*, 47:381–391, 1954.

[24] K. Henmi and T. Yoshikawa. Virtual lesson and its application to virtual calligraphy system. In *Proceedings of IEEE International Conference on Robotics and Automation (ICRA)*, pages 1275–1280, 1998.

[25] A. Israr, S. Choi, and H. Z. Tan. Detection threshold and mechanical impedance of the hand in a pen-hold posture. In *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 472–477, 2006.

[26] A. Israr, S. Choi, and H. Z. Tan. Mechanical impedance of the hand holding a spherical tool at threshold and suprathreshold stimulation levels. In *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems.World Haptics 07*, pages 56–60, 2007.

[27] B. Khademian and K. Hashtrudi-Zaad. Performance issues in collaborative haptic training. In *Proceedings of IEEE International Conference on Robotics and Automation (ICRA)*, pages 3257–3262, 2007.

[28] M. Kocsis, H. Z. Tan, and B. D. Adelstein. Discriminability of real and virtual surfaces with triangular gratings. In *Proceedings of Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 348–353, 2007.

[29] G. S. Lee and B. Hannaford. Anisotropies of touch in haptic icon exploration. In *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 2713–2717, 2003.

[30] G. S. Lee and B. Hannaford. Preliminary two dimensional haptic thresholds and task performance enhancements. In *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 85–90, 2003.

[31] H. Levitt. Transformed up-down methods in psychoacoustics. *Acoustical Society of America*, 49:467–476, 1971.

[32] J. Lieberman and C. Breazeal. Development of a wearable vibrotactile feedback suit for accelerated human motor learning. In *Proceedings of IEEE International Conference on Robotics and Automation (ICRA)*, pages 4001–4006, 2007.

[33] J. Liu, J. L. Emken, S. C. Cramer, and D. J. Reinkensmeyer. Learning to perform a novel movement pattern using haptic. In *Proceedings of International Conference on Rehabilitation Robotics (ICORR)*, pages 37–40, 2005.

[34] A. S. Merians, H. Poizner, R. Boian, G. Burdea, and S. Adamovich. Sensorimotor training in a virtual reality environment: Does it improve functional recovery post-stroke? *Neurorehabilitation and Neural Repair*, 20(2):252–267, 2006.

[35] D. Morris, H. Z. Tan, F. Barbagli, T. Chang, and K. Salisbury. Haptic feedback enhances force skill learning. In *Proceedings of Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems.World Haptics 07*, pages 21–26, 2007.

[36] C. Muller-Tomfelde. Interaction sound feedback in a haptic virtual environment to improve motor skill acquisition. In *Proceedings of International Conference on Auditory Display (ICAD)*, 2004.

[37] J. Mullins, C. Mawson, and S. Nahavandi. Haptic handwriting aid for training and rehabilitation. In *Proceedings of IEEE International Conference on Systems, Man and Cybernetics*, pages 2690–2694, 2005.

[38] F. A. Mussa-Ivaldi and J. L. Patton. Robots can teach people how to move their arm. In *Proceedings of IEEE International Conference on Robotics and Automation (ICRA)*, pages 300–305, 2000.

[39] M. Nishida and MP. Walker. Daytime naps, motor memory consolidation and regionally specific sleep spindles. *PLoS One*, 2, 2002.

[40] I. Oakley, S. A. Brewster, and P. D. Gray. Can you feel the force? an investigation of haptic collaboration in shared editors. In *Proceedings of Eurohaptics*, pages 54–59, 2001.

[41] B. Plimmer, A. Crossan, and S. A. Brewster. Computer supported non-visual signature training. In *Proceedings of First International Workshop in Haptic and Audio Interaction Design (HAID2006)*, 2006.

[42] G. L. Poling, J. M. Weisenberger, and T. Kerwin. The role of multisensory feedback in haptic surface perception. In *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 187–194, 2003.

[43] O. Portillo-Rodriguez, C. A. Avizzano, A. Chavez-Aguilar, M. Raspolli, S. Marcheschi, and M. Bergamasco. Haptic desktop: The virtual assistant designer. In *Proceedings of The 2nd IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications*, pages 1–6, 2006.

[44] G. Robles-De-La-Torre and V. Hayward. Force can overcome object geometry in the perception of shape through active touch. *Nature*, 412:445–448, 2001.

[45] M. Salada, P. Vishton, J. E. Colgate, and E. Frankel. Two experiments on the perception of slip at the fingertip. In *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 146–153, 2004.

[46] J. Solis, C. A. Avizzano, and M. Bergamasco. Teaching to write japanese characters using a haptic interface. In *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 255–262, 2002.

[47] J. Solis, C. A. Avizzano, and M. Bergamasco. Validating a skill transfer system based on reactive robots technology. In *Proceedings of IEEE International Workshop on Robot and Human Interactive Communication (ROMAN)*, pages 175–180, 2003.

[48] G. Srimathveeravalli, V. Gourishankar, and K. Thenkurussi. Haptic attributes and human motor skills. In *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 453–459, 2006.

[49] G. Srimathveeravalli and K. Thenkurussi. Motor skill training assistance using haptic attributes. In *Proceedings of First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 452–457, 2005.

[50] N. D. Sylvester and W. R. Provancher. Effects of longitudinal skin stretch on the perception of friction. In *Proceedings of Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 07*, pages 373–378, 2007.

[51] H. Z. Tan, B. D. Adelstein, R. Traylor, M. Kocsis, and E. D. Hirleman. Discrimination of real and virtual high-definition textured surfaces. In *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 3–9, 2006.

[52] H. Z. Tan, F. Barbagli, K. Salisbury, C. Ho, and C. Spence. Force-direction discrimination is not influenced by reference force direction. *Haptics-e*, 4(1), 2006.

[53] C. L. Tao, E. Burdet, and H. P. Lim. A robotic teacher of chinese handwriting. In *Proceedings of Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 335–341, 2002.

[54] M. Tavakoli, R. V. Patel, and M. Moallem. A haptic interface for computer-integrated endoscopic surgery and training. *Virtual Reality*, 9:160–176, 2006.

[55] R. Taylor, M. Kazakevich adn P. Boulanger, M. Garcia, and W. F. Bischof. Multimodal interface for fluid dynamics simulations using 3-d localized sound. In *Proceedings of International Symposium on Smart Graphics*, pages 182–187, 2007.

[56] SensAble Technologies. www.sensable.com, 1993.

[57] D. Toffin, J. McIntyre, J. Droulez, A. Kemeny, and A. Berthoz. Perception and reproduction of force direction in the horizontal plane. *Neurophysiology*, 90(5):3040–3053, 2003.

[58] B. Unger, R. Hollis, and R. Klatzky. Jnd analysis of texture roughness perception using a magnetic levitation haptic device. In *Proceedings of Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 07*, pages 9–14, 2007.

[59] L. G. Ungerleider, J. Doyon, and A. Karni. Imaging brain plasticity during motor skill learning. *Neurobiology of Learning and Memory*, 78:553–564, 2002.

[60] L. Walker and H. Z. Tan. A perceptual study of haptic rendering of surface topography when both surface height and stiffness vary. In *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 138–145, 2004.

[61] M. P. Walker, T. Brakefield, J. Seidmann, A. Morgan, J. A. Hobson, and R. Stickgold. Sleep and the time course of motor skill learning. *Neurobiology of Learning and Memory*, 10:275–284, 2002.

[62] D. Wang, Y. Zhang, and C. Yao. Stroke-based modeling and haptic skill display for chinese calligraphy. *Virtual Reality*, 9(2):118–132, 2006.

[63] E. H. Weber. *De pulsu, resorptione, audita et tactu.* Annotationes anatomicae et physiologicae, Leipzig, Koehler (Translated by H.E. Ross, Academic Press, New York, 1978), 1834.

[64] R. W. Webster, D. I. Zimmerman, B. J. Mohler, M. G. Melkonian, and R. S. Haluck. A prototype haptic suturing simulator. *Medicine Meets Virtual Reality*, 81:567–569, 2001.

[65] R. L. Williams, M. Srivastava, and R. Conaster. Implementation and evaluation of a haptic playback system. *Haptics-e*, 3(3):160–176, 2004.

[66] S. Yang, H. Z. Tan, P. Buttolo, M. R. Johnston, and Z. Pizlo. Thresholds for dynamic changes in a rotary switch. In *Proceedings of Eurohaptics*, pages 343–350, 2003.

[67] Y. H. Yoo and W. Bruns. Motor skill learning with force feedback in mixed reality. In *Proceedings of 16th IFAC World Congress*, 2005.