ABSTRACT

ZHU, BIWEN. Assessing the Effects of Feedback Type and Modality on Motor Skill Learning and Human Motivation. (Under the direction of Dr. David B. Kaber).

Two types of feedback, including knowledge of results (KR) and knowledge of performance (KP) are commonly delivered in motor training through various sensory modalities (i.e., visual, auditory or kinesthetic). For example, therapists use robots or virtual reality (VR) displays to deliver multimodal performance feedback to patients in real time. Such feedback has been found to increase learning and motor skill recovery as compared with traditional physical training. Similarly, industrial managers use task outcome feedback to sustain operator work motivation and ensure overall productivity, as well as to reduce learning periods for new work tasks. However, there is a lack of a design basis for such sensory feedback systems to optimize motor learning and motivation.

The objective of this study was to investigate the effects of feedback type and feedback modality on motor skill learning and motivation. To address this, 24 right-handed participants were recruited for a computer-based psychomotor training task (a Fitts' task) using a contemporary (Novint Falcon) haptic interface. During task performance, feedback was provided on whether a target was acquired (KR), on the process of acquiring a target (KP), or on both task outcomes and movement processes (combo). KP, KR or combo feedback were presented to subjects through one of three sensory modalities, including visual, auditory or haptic. Task performance and motor control data were collected on each trial as a basis for calculating learning rate and skill retention.

Results showed that KP was superior to KR in terms of comprehensive task performance retention (i.e., considering both speed and accuracy); whereas, KR was good for

training only a specific aspect of task performance (e.g., accuracy). A combination of KP and KR through the same modality was not found to produce an additive positive learning effect for task performance. Instead, such feedback supported to a greater extent skill retention in terms of jerkiness of control, especially with the haptic modality. With respect to the feedback modality effect, results revealed enhanced learning effects of haptic or auditory cues (over visual cues), but only with the existence of multiple information cues.

Results showed that task outcome related feedback (e.g., KR or combo) was better than process-based feedback (i.e., KP) in terms of sustaining human intrinsic motivation during the training period. The haptic modality was also found to have stronger motivating effect than the visual or auditory modalities. In addition to these results, a medium level motivational state was found to be more helpful for increasing learning rate in terms of reducing motion path deviations, as compared with low or high motivational states.

The research findings resulted in a set of feedback design guidelines for training systems to be used in motor rehabilitation or skill development for industrial tasks. Examples of how to apply these recommendations to existing systems were described. The current research also developed and validated a novel approach/protocol for studying motor learning/retention process as based on industrial learning curve theory. This methodology could be extended to other applied motor learning research studies.

Assessing the Effects of Feedback Type and Modality on Motor Skill Learning and Human Motivation

by
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BIOGRAPHY

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ANVOA	Analysis of variance
ATMR	Adjusted trial miss rate
CIMT	Constraint-Induced Movement Therapy
Dof	Degree of freedom
EEG	Electroencephalography
EMG	Electromyogram
GSR	Galvanic skin conductance
HMD	Head mounted display
HR	Heart rate
HIP	Human information processing
ID	Index of difficulty
IDE	Integrated development environment
IMI	Intrinsic Motivation Inventory
KR	Knowledge of results
KP	Knowledge of performance
LTM	Long-term memory
MT	Movement time
RMA	Rivermead Motor Assessment
ROCF	Rey–Osterrieth Complex Figure
SAM	Self-Assessment Manikin
SDT	Self-determination theory
STSS	Short term sensory store
TBI	Traumatic Brain Injury
TMT	Total movement time
WM	Working memory
VR	Virtual reality

CHAPTER 1: INTRODUCTION

Manual motor skill learning, such as industrial assembly job learning, typically involves repetitive training of limb movements over time. Two major challenges are associated with such skill learning. First, training of new skills can be boring and operators may lack interest. Second, given the fact that operators are paid by the time they spend learning the job (rather than the number of units produced) before mastering the skill, they lack monetary motivation to produce more units or to accelerate the learning process. As a consequence, a company has to pay an additional expense for slow learning and low worker motivation.

This phenomenon appears to be more prominent in the case of motor rehabilitation training, a special category of motor learning. In one newly developed training therapy (Taub, Uswatte & Pidikiti, 1999), patients are subjected to concentrated, repetitive training of an impaired limb for 6 hours per day over 2 to 3 week periods. It is possible that patients feel a sense of frustration when they fail to complete a required limb movement. This could lead to temporarily reduced levels of motivation or even permanent termination of the therapy. In addition, most physical therapies require at least one therapist to work with a patient during the training process. High training costs can occur if rehabilitation learning is slow.

In order to address these issues, various forms of task feedback have been used in motor skill training to sustain motivation and support learning. In the physical rehabilitation area, performance and kinematic feedback are presented to patients using robots or virtual reality (VR) displays. Similarly, workers in the industrial settings typically receive feedback when learning tasks via video replay or general comments from a trainer. Such feedback methods can be categorized into two groups. One group emphasizes feedback on task

outcomes, whereas the other group focuses more on the state of limb movement during task performance (see details in Chapter 2). Prior studies have attempted to compare the two feedback groups with respect to their influence on motor learning and retention (M. Cirstea & Levin, 2007). However, they failed to control the form or modality of feedback conditions. Therefore, there is a lack of an empirical basis for feedback design to promote motivation and learning during motor skill training.

The objective of this research was to compare the utility of various types of sensory feedback on manual motor learning and human motivation. The results of this study could be used to redesign current rehabilitation training systems, as well as optimize physical task training programs in industrial environments.

1.1. Motor learning: Definitions and theories

1.1.1. Definition of motor learning

Schmidt and Lee (2005) defined motor learning as "*a set of processes associated with practice or experience leading to relatively permanent changes in the capability for movement*". Several key characteristics of motor learning can be revealed from this definition. First, motor learning is always associated with a set of internal events, occurrences or processes. Understanding these processes is more critical to training design than simply observing changes in motor capabilities *per se*. For example, it would be beneficial to know what processes are involved when muscle programs are triggered by sensory inputs and are further retrieved from long term memory. Second, the amount of practice is the most influential variable in motor learning. Permanent learning usually cannot be achieved through direct observation of performance by others. Third, motor learning results in relatively

permanent changes in motor behavior. It leads to automaticity and consistency in motor planning as well as motor control. This also suggests that techniques on measuring learning are quite different than performance measures, which is the focus of traditional human factors experiments.

1.1.2. Learning and performance variables

In motor skill learning studies, anticipated learning and performance effects should be clearly identified. According to Schmidt and Lee (2005), a learning variable facilitates long-term skill retention whereas a performance variable facilitates more temporary skill acquisition. Previous studies have found that some task variable manipulations may be good for temporary performance acquisition, but they may also degrade long-term learning and retention. For example, Shea and Morgan (1979) asked subjects to learn to respond to color-coded visual signals and make corresponding movements with one arm to four specific targets (e.g., red signal on, follow movement Trajectory #1). Subjects were separated into either a blocked practice condition or random practice condition. In the blocked practice condition, subjects completed all trials of one movement trajectory before attempting a second trajectory. In the random practice condition, the movement trajectory was switched on each trial. Results showed that although random practice led to increased reaction time, as compared with blocked practice (during the skill acquisition period), it eventually resulted in better performance in a retention period. In fact, the positive performance effects of the blocked practice condition were found to almost completely disappear during the retention period, indicating that block practice was a condition variable facilitating temporary performance, but not learning.

In another similar study by Armstrong (1970), subjects were instructed to make an elbow movement with a specific spatial-temporal pattern. Average integrated absolute position error from the template pattern was collected as the main performance measure. The author separated subjects into three different feedback groups, including: (1) terminal kinematic feedback on subject movement (after each trial) and template pattern movement (after a set of 15 trials); (2) concurrent visual kinematic feedback on both subject movement and the movement of the pattern template; and (3) automatic guidance by a mechanical device. Results showed that concurrent kinematic feedback and automatic guidance led to lower errors in the skill acquisition period, whereas terminal kinematic feedback had a significantly greater learning effect during retention. This study also suggested that the timing of feedback delivery (concurrent versus terminal) significantly influences learning.

The above review results suggested the processes associated with long-term skill learning and short-term performance acquisition might not be the same. Therefore, there is a need for future studies to investigate key characteristics that discriminate a performance variable from learning variable. It is possible that a learning variable facilitates greater memory usage and task procedure knowledge formation, whereas a performance variable may have more of an impact on the flow of human information processing. The present study focused mainly on motor learning response, and performance data was collected as a basis for measuring learning.

1.1.3. The three-stage learning process theory

Earlier researchers have agreed that learners appear to pass through distinct stages when they practice a skill (Schmidt & Lee, 2005). For example, Snoddy (1926) said motor learning

involves two phases: adaptation and facilitation. In the first stage, learners need to acquire the neuromuscular pattern for task performance, whereas in the second stage, they focus more on improving the efficiency of the pattern. Other researchers (e.g., Anderson [1982, 2000]) further refined Snoddy's model and discussed motor learning in terms of three phases of practice. These include a cognitive phase, associative phase, and autonomous phase.

When the learner is exposed to a new task, considerable cognitive activities are required before (s)he initiates a movement. For example, (s)he needs to understand what is to be done, how the performance is to be scored and how to attempt the first few trials. The success of motor learning in this cognitive stage largely depends on whether or not the learner can quickly determine an appropriate strategy for the new task. Anderson argued that most improvements in this first stage are verbal-cognitive in nature; this implies that verbal instruction and cognitive processing are key components to motor learning in this stage. Generation of motor patterns was not considered to be critical here.

Once a learner has determined the specific motor patterns for a task, the associative phase begins in which subtle adjustments are made in how the skill is performed. The learner concentrates on how to execute particular movement patterns and how to make changes based on various forms of feedback, rather than determining which pattern should be used. Performance in this stage improves gradually and movements become more consistent.

In the third phase of motor learning, subject skill becomes largely automatic in the sense that they can perform the task fairly well without interference from other simultaneous activities. Task-related mental models are developed and can be processed with minimal time. In this phase, high-level skill is achieved and can persist for a long period of time.

Rehabilitation to address specific types of injuries, such as stroke and traumatic brain injury (TBI), and associated disabilities can also be viewed as a three stage-learning process. For example, Wolpert and Ghahramani (2000) and Krakauer (2006) argued that physical rehabilitation is a process of motor relearning that includes: (1) planning and controlling a series of motor commands, (2) estimating and predicting motor state errors, and (3) forming task-related internal mental models. The planning stage involves specifying high-level task goals and associating them with low-level controls (i.e., muscle activation patterns leading to specific joint rotations and positions). In the biomechanics or movement science areas, controls are commonly related to both the kinematic (geometry and speed) and dynamic (force) aspects of a movement. Learning a skill can be viewed as practice-dependent reduction of control errors detected through sensory feedback. Well-learned movements become automatic and are later turned into parts of motor programs. Internal mental models are useful for transforming and applying the particular procedural knowledge to more general tasks. In short, all the stages of motor learning (i.e., planning, controlling, estimation and prediction) can be represented and explained in terms of cognitive information processing.

Different types of processing capabilities have been found to be associated with the three stages of motor leaning (Ackerman, 1990). Ackerman conducted a series of experiments in which he first asked subjects to perform simple reaction-time tasks (e.g., press keypad 1 in response to visual cue “#1” on the screen). Due to the trivial nature of the tasks, subjects determined what to do with no difficulty. Therefore, they were expected to perform as if starting in the second phase of motor learning. However, beginning from a seventh session, the task was switched to a more complicated version in which subjects had to press a

key designated by a two-letter abbreviation code. The two letters indicated the numeric keypad *row* and *column,* respectively (e.g., UR meant upper row and right column, indicting the “9” key). This task required considerable cognitive skill, forcing learners back into the first phase of practice. Finally, the third phase of motor learning was identified when learners achieved asymptotic performance.

Ackerman collected data on subjects, including general intellectual abilities, perceptual speed abilities, as well as psychomotor abilities. Results showed that *intellectual abilities* (i.e., information processing skills) were highly correlated with performance score (i.e., reaction time), and were regarded as key learning determinants in the first phase. However, these abilities were replaced by *perceptual speed abilities* in the associative learning stage. Individual differences in *psychomotor abilities* appeared to be most important during the autonomous stage of learning. The current proposed study focused on the “*associative stage*” of the learning process. Anderson’s research provides a sound theoretical basis for expecting monotonic performance improvements over test trials during this learning stage.

1.1.4. Measures of motor learning

Retention tests are the basic and most well known measures of motor learning at the behavioral level (Schmidt & Lee, 2005). Using this technique, subjects need to perform the same task after some retention interval and performance data are collected. Any independent variable manipulated in the training period (e.g., knowledge of results) should be left intact for the retention tests (Christina, 1997). Christina and Shea (1993) suggested that both immediate and delayed retention tests be included in motor learning experiments. The

retention interval for the immediate retention test should be the same as the inter-trial interval during the skill training phase of the experiment. The delayed retention interval can range from as little as 5 minutes to days, depending on the study. If performance level on the retention test is as proficient as it was immediately after the end of the original learning, this indicates no memory loss. On the other hand, if performance in retention is poor, we might conclude that certain learning was lost. However, the performance degradation may also occur due to factors other than motor memory loss, such as fatigue and low motivation. Therefore, test conditions for any motor learning studies should be configured (or designed) to minimize such temporary factors.

Transfer tests are similar to retention tests except that subjects are tested under a new condition or task after the retention interval. The amount of transfer depends largely on the similarity of the two tasks and is commonly positive. Negative transfer is also possible in which the experience of one task in training can cause skill loss in another. This usually occurs when the two tasks are similar in gross movement structure yet incompatible in skill requirement (e.g., tennis versus badminton).

Learning curve analysis also provides a structured, mathematical approach to predict how task performance improves over time (Wright, 1936). It can be used to predict how much time an operator needs to achieve asymptotic performance during training of new skills. The standard equations used to determine learning percentage are as follows:

$$Y_n = Y_1 n^b, or\ b = \frac{\log(Y_n) - \log(Y_1)}{\log(n)}$$

$$Learning\ percentage = K = 100 * 2^b, where\ Y_n$$

$$= performance\ level\ (e.g., production\ time) at\ the\ n^{th}\ cycle$$

The original learning model by Wright (1936) stated that the direct labor man-hours necessary to complete a unit of production will decrease by a constant percentage each time the production quantity doubles. For example, if a learning model expects an 80% rate of learning, then when production doubles, the average unit time declines by 20%. In this sense, a smaller learning percentage (i.e., K) corresponds to a higher potential (or rate) for future learning, together with greater progressive improvements with production output (see Figure 1). This model can also be easily adapted to other tasks or scenarios in which the main performance measure is not "*production time*". For example, in a dart shooting context, Y_n would be total number of points one earned within three shots.

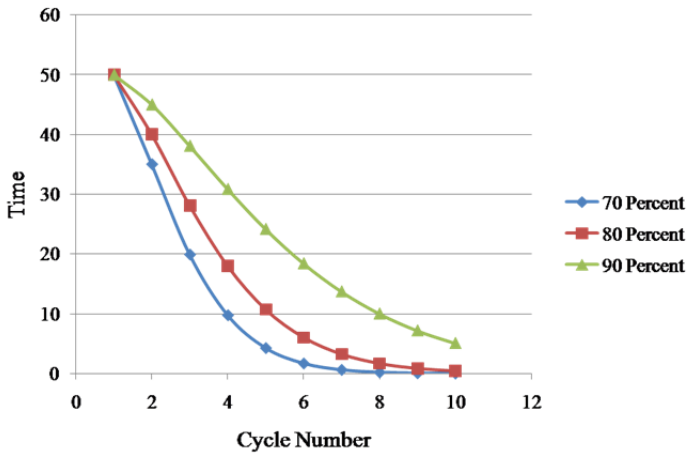

Figure 1. Simulated learning curve with three levels of learning percentage

Wright's model has also been modified for scenarios when breaks are involved during the learning (Hancock & Bayha, 1992). The fact is that humans forget some learning during task breaks and they start from a lower performance level after the break (see Figure 2). The difference in performance from continuous learning indicates the amount of skill loss (or the amount of remission, as labeled by Hancock and Bayha). Looking at the dashed curves in Figure 2, they represent learning curves for each continuous learning cycle without break. The shape of the curves does not change due to breaks. This suggests that although humans forget some of the learning during the break, the rate of learning does not change. In the present study, specific test conditions were applied in each of the learning periods. The slope of the learning curve was determined to identify differences among test conditions.

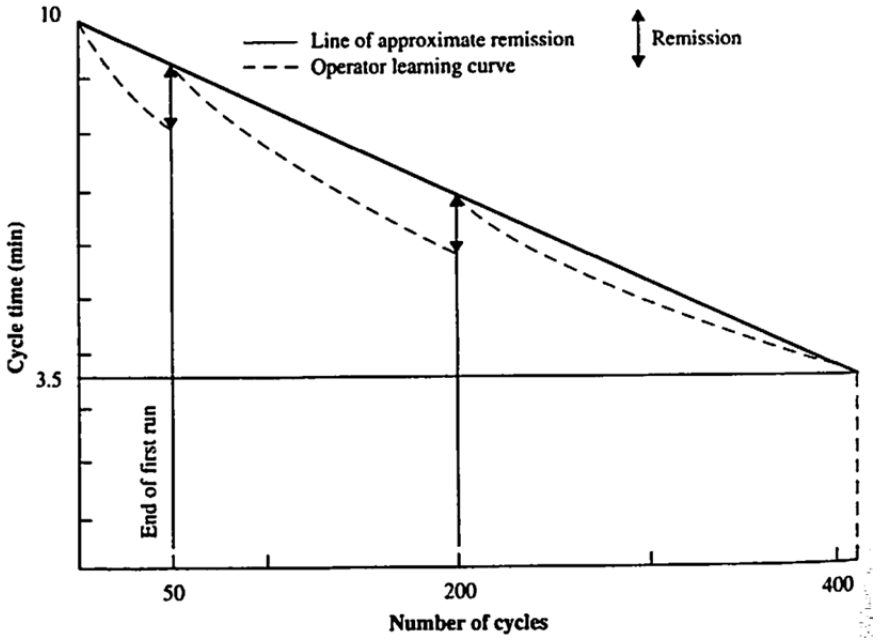

Figure 2. Learning curve with remission from Hancock and Bayha (1992)

Recently, learning curve techniques have been used in human factor experiments. For example, Anderson, Mirka et al. (2009) investigated how alternative keyboard designs

influence human learning of passage typing. They asked subjects to type a passage several times using each of the alternative keyboard designs. The order of the conditions was randomly assigned. The learning percentage for each of the keyboard designs was calculated for each individual. A repeated-measures ANOVA was used for inferential statistics. Results showed that a "fixed split" keyboard design led to the highest learning percentage (i.e., lowest learning rate) compared with other designs. This study was closely related to the present study and is referenced later.

1.1.5. Cognitive model of motor control and learning

Various computational models of learning have been developed to describe the underlying mechanisms of motor control in neurologic rehabilitation (Horak, 1991). For example, the reflex model (Easton, 1972) adopted a "bottom-up" approach, assuming that movement is the summation of reflexes in response to sensory inputs. This model posited that sensory input controls motor outputs and is necessary for movement generation. Hierarchical models (Reed, 1982), on the other hand, take a top-down approach and argue that the central nervous system controls muscle activation patterns. More modern studies view the movement control problem as a mix of feedback (reactive) and feedforward (predictive) control (Carolee-Winstein, Wing & Whitall, 2003). A "*feedforward internal model*" predicts movement kinematics and dynamics based on given command inputs; whereas, a "*feedback internal model*" transforms the desired movement consequences to specific motor commands. Considering a reaching and gripping task, one needs to use a feedforward model to estimate the most efficient reaching trajectory; one also needs a feedback model to adjust the motor command (e.g., force applied for gripping), based on error messages derived from sensory

inputs (e.g., an object sliding between the fingers). Various empirical studies have proved that these two mechanisms are fundamental to movement control and learning (see Carolee-Winstein, et al. [2003] for a review). These models provide a sound theoretical basis for hypotheses on feedback as an influential factor in motor skill learning and rehabilitation.

1.2. Rehabilitation: A special type of motor learning

Physical rehabilitation is regarded as a special category of motor learning and the study of rehabilitation has gained wide popularity in recent years. This section reviews several types of physical rehabilitation techniques, beginning with traditional physical therapies and making comparison with robotic or VR-based rehabilitation techniques. It is noted that augmented quantitative feedback is a main feature of newly developed rehabilitation techniques. However, the design of feedback in such systems lacks an empirical basis. This represents another motivation for the present research.

1.2.1. Physical therapy techniques

Motor recovery and relearning can be facilitated by active or passive repetitive training of an affected limb. This type of therapeutic training isolates muscle actions by focusing on individual movements with the objective of maximizing strength and use of the remaining motor units. For example, Butefisch et al. (1995) had 27 paraplegic patients perform repetitive hand and finger flexions and extensions against various loads for 3 weeks. They found that motor performance (e.g., grip strength and isometric hand extensions) improved significantly during the training period. Functional motor capacity based on Rivermead Motor Assessment (i.e., RMA) also improved by the end of the training. RMA is a standard

measure that assesses the functional motor performance of patients with stroke. It was developed for both clinical and research use (Collen, Wade, Robb & Bradshaw, 1991).

There is also evidence that task-oriented intervention improves motor recovery significantly in terms of restoring balance and strengthening lower limb function (Van Peppen, et al., 2004). Such training protocols focus on facilitating normal movement patterns and helping patients learn to achieve task goals rather than simply strengthening affected muscles. However, Higgins et al. (2006) found that an improvement in upper extremity function was not observed after task-oriented training. They argued, however, that outcome measures were not sensitive enough to detect small changes occurring at the level of arm performance. This also suggests that the utility of particular rehabilitation techniques may vary according to affected limb.

A relatively modern class of rehabilitation techniques, referred to as Constraint-Induced Movement Therapy (CIMT or CI), has gained a large amount of attention and showed meaningful gains even for chronic stroke or cerebrovascular accident patients (Taub, et al., 1999). This technique involves constraining movements of the less-affected limb for 90% of waking hours, while intensively practicing the affected limb for 6 hours per day. This therapy was designed to help patients in the chronic stage of stroke to overcome "*learned non-use*" of the affected limb and to prevent patients in an acute stage from adopting "*compensatory*" strategies. In general, this type of training lasts about 2 weeks and its therapeutic effects can be transferred to real world activities for at least 2 years (Miltner, Bauder, Sommer, Dettmers & Taub, 1999).

Neuromuscular stimulation techniques have been found to be helpful for motor and functional recovery for stroke patients with limited wrist and finger extension capabilities (Chae, et al., 1998). In one study, 28 patients received electromyogram-triggered surface neuromuscular stimulation to produce wrist and finger extension exercises for 15 days. Significantly more gains in motor function were found for the treatment group as compared with a control group receiving "*placebo*" stimulation.

In general, the above techniques are helpful for motor skill recovery and relearning to different degrees. However, these manually assisted protocols are commonly labor intensive and require a high degree of repetition. Motor relearning can be compromised if task repetitions are not performed. Moreover, it is not just repetition alone that produces motor learning (Holden, 2005). Repetition should be combined with incremental success (or performance knowledge) in a task to sustain patient motivation and attention. In normal nerve systems, this is normally achieved by intrinsic feedback from the sensory organs (e.g., vision). Stroke or brain-injured patients, however, might not be able to take full advantage of such mechanisms and may require additional augmented feedback (either from instrumentation or therapists). In the following sections, two additional classes of rehabilitation techniques are described, including robot assisted therapy and VR-based therapy, which focus on the three key concepts of motor learning: repetition, feedback and motivation.

1.2.2. Robotic-based rehabilitation for upper limbs

Several robotic rehabilitation devices for upper limb motor skill recovery have been developed and tested in randomized clinical settings, including MIME (Burgar, Lum, Shor &

Van der Loos, 2000), MIT-MANUS (Krebs, Hogan, Aisen & Volpe, 1998), ARM Guide (Reinkensmeyer, et al., 2000), and Gentle/s (Loureiro, Amirabdollahian, Topping, Driessen & Harwin, 2003). The majority of these studies have involved assessing the effects of repetitive robotic training of a patient's arm, shoulder or elbow movement for about 4–6 months. Data on motor control, muscular-skeletal performance, functional abilities and independence have been recorded and compared with control groups (e.g., traditional manual physical training). General evidence was found that robot-aided therapy of upper-extremity movement improves both short-term and long-term motor functions, but not daily functional abilities (Kwakkel, Kollen & Krebs, 2008; Prange, Jannink, Groothuis-Oudshoorn, Hermens & IJzerman, 2006). Instead of re-reviewing clinical evaluation results for each robot training device, the following discussion focuses on the characteristics of robotic devices and how they are different from standard training methods.

MIME is a bimanual, mirror-image and patient controlled device for reaching and tracing tasks (Burgar, et al., 2000). A patient's hands are attached to two separate robot end-effectors during the training. The robot can continuously move the paretic limb to the mirror-image position of the opposite, less affected limb. Such mirror-style training has proved to be helpful for motor recovery and has a sound neurological basis (Ramachandran & Altschuler, 2009). Moreover, subjects can feel the robot's velocity-sensitive resistance (i.e., force feedback) when producing a force in the direction of movement. Feedback on fractions of the movement completed and the remaining time needed to complete a reaching task can also be presented to patients to sustain motivation. All these features are not easily replicated in standard physical training.

MIT-MANUS (Krebs, et al., 1998) is another device that can move, guide or perturb the movement of a patient's upper limb using impedance-control. It is a robotic training task with gaming components including drawing circles, stars, squares, diamonds, and navigating through windows. Feedback on performance errors can also be directly derived from a computer screen. These unique components are regarded as key design strategies that could enhance patient motivation when exercising with MIT-MANUS. Related to this study, Colombo et al. (2007) developed two rehabilitation robots for spatial object tracking tasks (one for wrist training and the other for elbow-shoulder training). They suggested that the design of the rehabilitation task should be "*simple*" and easy to learn to reduce "start-up" effort. High quality feedback information about task performance is also considered essential for sustaining motivation. Quantity of feedback should also be designed to prevent "*information overload"*.

1.2.3. VR-based rehabilitation for upper-limb movement

There is also wide range of applications of VR technologies in the field of motor rehabilitation (e.g., Jack et al., 2001). The key additional feature of VR is that patients exercise in an immersive virtual environment rather than in the real world. To achieve this goal, a 3-D stereo display is essential for viewing. Such displays are integrated with light-shutter glasses, or more expensive head-mounted VR displays (HMD), or can be used as alternatives to room-sized CAVE™ systems. Such additional features make VR technology an easy and more effective tool for addressing essential human motor learning elements, including (1) repetitive practice, (2) feedback, and (3) motivation to endure practice. Evidence has been found that humans can learn motor skills in virtual environments and

transfer them to the real world (Lintern, Roscoe, Koonce & Segal, 1990; Theasby, 1992). A contemporary review of VR rehabilitation can be found in Holden (2005).

Gentle/s (Loureiro, et al., 2003) is an appealing robot device for training reaching tasks for stroke patients, which also integrates a haptic device and VR technology for presenting various types of sensory feedback. Visual, auditory, haptic and performance cues are presented to subjects in real time during training. For example, visual cues are used to present a target object and virtual scene; haptic cues are used when manipulation of objects is required as part of the training; auditory cues are used to present encouraging words; and performance cues are used to indicate reaching errors. In addition to this, the system is also capable of creating different virtual scenes (e.g., an empty room, real room or decorated room) to represent real reaching scenarios. Objective analytical methods for evaluating a patient's reaching performance are also possible during off-line assessment. All these features are unique and cannot be easily replicated in standard physical training.

In summary, the above reviews suggest that augmented feedback is a unique feature in robot-aided or VR-aided rehabilitation, and might facilitate enhanced motivation and additional motor learning as compared with manual physical therapy. However, there are few feedback design guidelines for these systems. There is also a need to use standardized tasks for rehabilitation training to support meta-comparisons across studies. In the next Chapter, a rough taxonomy of augmented feedback is provided to further categorize methods as either knowledge of results (KR) or knowledge of performance (KP). The learning benefits of the two general feedback types are compared. Related issues such as feedback delivery, modality and schedule are also discussed.

CHAPTER 2: FEEDBACK TYPES, MOTOR LEARING AND MOTIVATION

2.1. Feedback types and motor learning

Motor learning feedback can be classified as either “intrinsic” or “augmented” (van Vliet & Wulf, 2006). Intrinsic feedback refers to human sensory or perceptual information that is available as a result of movement being performed. For example, a basketball player sees that he has missed a shot. Augmented feedback (i.e., extrinsic feedback), however, comes from external sources (e.g., therapies or equipment) and is usually provided in addition to intrinsic feedback during training. For example, encouragement from a therapist can be viewed as augmented feedback.

Augmented feedback on task performance is also frequently used by therapists or coaches during training (McMorris & Hale, 2006). The forms can either be prescriptive (describing performance errors and ways to correct them; e.g., “*you are approaching a foot too far, reduce the speed a little bit”*) or descriptive (describing errors only). Prescriptive feedback is better for beginners who need to know what’s wrong with their behavior and how to correct it, whereas experienced performers benefit more from descriptive feedback. Such feedback is commonly given verbally by the trainer (e.g., motivational encouragement), or visually through video or demonstration. Moreover, augmented feedback can be delivered concurrently during training (instant feedback), at the termination of several trials (summary feedback), or in faded fashion (initially every trial, then after several trials) based on learning. In some situations, performance feedback is given only if performance falls outside a threshold set by the trainer (i.e., bandwidth feedback). The relative benefits of various

feedback schedules have been extensively studied and are covered in a review by van Vliet and Wulf (2006).

2.1.1. A taxonomy of augmented feedback

In general, augmented performance feedback can be further separated into knowledge of performance (KP) or knowledge of results (KR) (Magill, 2004) (Figure 3). KP is information concerning the nature of the movement pattern or process of which a performer is only vaguely aware (e.g., gymnist limb position during training), whereas KR is verbal (or verbalizabled), post-movement information on the outcomes of an action in terms of an environment goal (e.g., “you were off the target by 3 inches”). The content of KR might change according to different goals. The content of KP may also change depending on what aspect of movement (i.e., kinematic or kinetic) is more critical for learning. KR cannot contain information about the movement itself. Instead, it should contain error–correction cues (i.e., the amount of error and direction of error) for performers for the next trial. Depending on the specific training goals, KR can be delivered in terms of a discrete measurement (i.e., success or failure) or continuous measurement (i.e., smoothness, deviation, etc.). In many everyday situations, KR tends to be redundant with information derived from intrinsic feedback through kinesthetic, visual or auditory channels, and this might compromise further motor learning. For example, Platz and Winter (2001) found that additional information from KR did not enhance learning since the chosen tasks already had inherent information about movement outcomes. Therefore, KP is more commonly provided to athletes or patients during training in natural settings (CJ Winstein, 1991), as knowledge of the movement patterns are more difficult to obtain intrinsically.

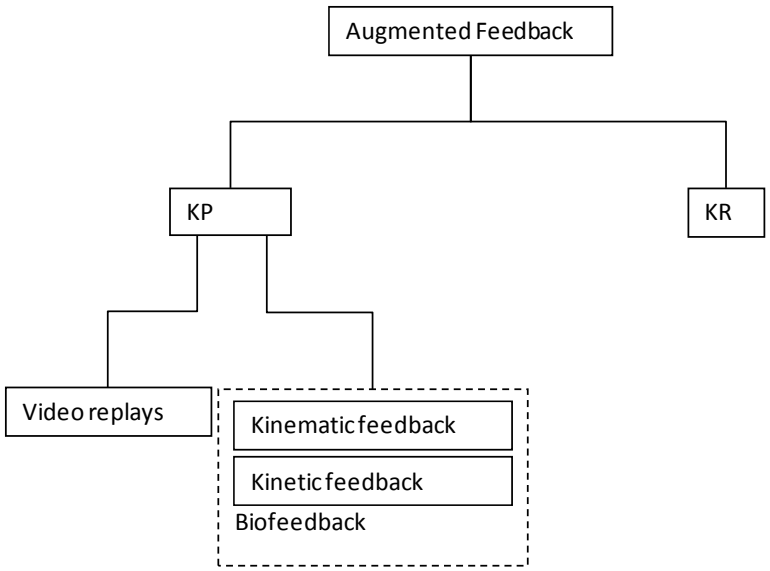

Figure 3. Taxonomy of augmented feedback

One common way for presenting KP to learners is the use of videotape replays. Replays can be of a learner's own performance, or the performances from a domain model or expert. Such KP is easy to deliver; however, it may contain too much irrelevant information for the learner. Kernodle and Carlton (1992) found that videotapes with additional directed viewing cues resulted in greater improvements in throwing performance as compared with a simple videotape feedback condition. The videotape alone was found to be no better than simply providing KR. Such results suggest that the content of videotape KP should be specific to key motor movement joints.

Another type of KP is called kinematic feedback, which involves the presentation of pure movement information such as position, time, velocity and patterns of coordination to trainees. They inform the learner of aspects of the movement pattern that may not be directly observable. However, the benefits of kinematic KP depend on a number of factors, including the nature of the task goals and the relevance of KP information to the goal. If the uniqueness

of the kinematic KP is not apparent as compared with less precise KR feedback, its effectiveness in motor learning might not be so obvious. For example, Swinnen et al. (1993) asked subjects to practice a discrete, bimanual coordination task. An elbow flexion movement was made in the left limb, whereas a flexion-extension-flexion movement was made in the right limb. Subjects were divided into a KR group (a simple outcome about the coordination performance) or a KP group (a precise representation of the profile of limb movement). Results showed that learning was equal between the two groups. This might be due to the kinematic feedback manipulation corresponding to the goal of the task (presented in terms of KR). The subjects in the KP condition could mentally calculate the KR score by comparing the profiles for the two limbs, and they attempted similar strategies to the task as those subjects in the KR group.

Related to kinematic KP, kinetic KP provides information about the forces that are produced during movements. The forces recorded over time provide a *force-time curve* that can be presented to the trainee after each trial. If the task goal is force-related (e.g., to produce a maximum impulse), such feedback would be understandable for trainees. In other tasks, directed cues should be provided by the instructors so that trainees can focus on the most important aspects of the *force-time curve*.

Both kinematic and kinetic KP are very similar to the concept of biofeedback. Biofeedback can be defined as the use of equipment to make covert physiological processes overt (obvious) to patients, and help them to learn self-control of these responses (Huang, Wolf & He, 2006). Typical information fed back to patients includes electromyogram (EMG; Wolf & Binder-Macleod, 1983), joint angle and limb position (Dursun, Hamamci, Donmez,

Tuzunalp & Cakci, 1996), pressure or force applied (Lars, 2007; Nichols, 1997), or electroencephalography (EEG; Thatcher, 2000), etc. This information is commonly presented in analog, digital or binary forms though visual display. It can also be presented in terms of auditory pitch (or volume) or mechanical tactile simulations. Traditional biofeedback studies usually have patients perform a simple movement unrelated to the activities of daily living (Huang, et al., 2006). As a consequence, the overall effect of traditional biofeedback training on motor recovery is still inconsistent (Glanz, et al., 1995; Van Dijk, Jannink & Hermens, 2005). Modern perspectives on biofeedback focus more on task-oriented dynamic biofeedback (Huang, et al., 2005). Such feedback integrates multiple variables that characterize the task and provide meaningful and easy-to-understand information to patients. This approach has the advantage of not overwhelming a patient's perception and cognitive ability.

2.1.2. KP and KR in the ergonomics area

The concept of KR also appears quite often in ergonomics research. Salvendy (1997) defined it as outcome related feedback. For example, he mentioned that feedback or reinforcement that is given to students to tell them how well they performed on the task is a typical form of KR in educational environments. According to his definition, KR could be either synchronous or asynchronous with performance. For example, if you asked subjects to continuously perform 50 trials of a discrete movement task in a block of time, KR in terms of "*hit*" or "*miss*" could be delivered after each individual movement trial (i.e., synchronous with performance); or a summative outcome of "*hit rate*" could be delivered at the termination of the whole task (i.e., asynchronous with performance). Wickens and Hollands

(1999) suggested that KR offered while a skill is being performed may be less useful than immediately after skill completion, simply due to divided attention issue. Such characteristics of KR in the ergonomics area are comparable with the previous definition of KR from the motor science area.

However, KP has not been defined clearly in human factors research. The reason is that typical ergonomic experiments are commonly goal related and performance-based. Goal or outcome related performance feedback (i.e., KR) is usually manipulated as an independent variable. KP information about a movement process, such as eye tracking data, biofeedback data, etc. are usually collected as response variables. In the motor learning area, however, we are not only interested in performance outcomes relative to a goal, but also how the movement is performed during the process. Knowledge of the process is important for skill acquisition as well as long-term learning and retention. Therefore, both KP and KR are commonly investigated and manipulated as independent variables in the motor science field.

In Table 1, some examples of KP (and KR) content are provided for various motor tasks. Some examples represent real-world tasks (e.g., basketball shooting), whereas others represent typical psycho motor tasks in ergonomics experiments (e.g., discrete movement or Fitts' tasks). As can be seen from the literature, kinematic feedback is the most commonly manipulated form of KP for all tasks. This might be due to information (e.g., limb position and the amount of the force applied) being critical to motor skill acquisition and learning. Such forms of KP can be easily explained by coaches or therapists. Trainees can also compare their postural information with a domain expert model, which helps facilitate procedural knowledge formation. Furthermore, KP in this form can be easily delivered in a

computerized bio-tracking system, and this saves time either for experimental or real-world training purposes.

Table 1. Examples of KP and KR feedback in the motor science and ergonomics areas

Task	Goal	KR	KP
Shooting a basketball	Shoot the ball into the basket Shoot as many baskets as possible within a certain amount of time.	Miss/hit Hit rate within the time duration	The behavior of the limb during the shooting.
Flight task	To maintain a certain altitude	Percentage of time that the plane is above the threshold altitude	Current altitude of the plane
Non corrective linear positioning task	Reach the target position as close as possible	Deviation from the target position	Current position or speed of the lever
Fitts task	Make as many target hits as possible within a certain amount of time	The target hit rate	Current position of stylus or contact with a target

2.1.3. What's better for motor learning, KP or KR?

Both KP and KR are valuable for motor recovery and learning. For example, Wallace and Hagler (1979) found that motor learning was possible when only KR was provided to subjects, but to a lesser extent when compared with both KP and KR. In another study, Bilodeau et al. (1959) designed a lever-displacing task, in which KR was given as the amount and direction of the placement error. Progressive improvement in the KR group was found as compared with a non-improvement control group with no KR. Performance deterioration was also found after the withdrawal of KR.

Related to this, a more recent study (C. Cirstea, Ptito & Levin, 2006) recruited 37 chronic stroke patients and investigated how different types of augmented feedback affected motor recovery in a reaching task. Patients were assigned to either a KR group with movement precision feedback, a KP group with faded joint motion feedback, or a control group with no feedback. Kinematic as well as clinical assessment data were collected and

evaluated. It was found that kinematic gains in either the KR or KP groups exceeded those for the control group. In summary, these studies provide a sound empirical basis for feedback intervention in motor learning.

There is some evidence that the use of KP during repetitive movement practice results in better motor outcomes and learning as compared with KR. Zubiaur et al. (1999) compared the two types of feedback in a volleyball learning task. Both KP and KR were delivered at various points during the testing process. Statistical analysis revealed that KP tended to be more effective for learning than KR. Kernodle and Carlton (1992) further suggested augmented KP with additional cues (e.g., attention-focusing cues or error-correcting transitional information) were more effective for learning as compared with regular KP (or KR) in a "*throwing*" activity.

KP was also found to be superior to KR in the rehabilitation learning context. In one study, chronic stroke patients were randomly assigned to either a KR or KP group in a pointing task (M. Cirstea & Levin, 2007). Patients were required to complete 75 reaching and pointing tasks per session for a total of 10 sessions over a 2 week period. KP feedback on joint motion was delivered 27% of the time, whereas KR feedback on movement precision was provided 20% of the time. ANOVA results showed that the KP group resulted in both immediate and long-term increases in joint range as compared with the KR group. The KP group also achieved better inter-joint coordination and such motor improvements were retained in follow-up evaluations.

2.1.4. Limitations and weakness of past feedback studies

Various weaknesses exist in previous studies directly comparing KP with KR. First and most important, previous studies have failed to control the feedback resolution and synchronization during the feedback manipulation. For example, Cirstea and Levin (2007) used concurrent kinematic feedback (i.e., elbow and shoulder movement) as a way to represent KP. This provided much finer information for trainees as compared with reaching precision feedback provided as a form of KR (i.e., a number). Subjects receiving kinematic feedback (i.e., KP) might be able to extract meaningful information on how to correct reaching movements in follow-on trials. On the other hand, some subjects might feel puzzled or overwhelmed with such complex information and fail to process it at a high-level of detail. This means that great individual differences exist in processing feedback information with various complexities. Therefore, the resulting beneficial effects of KP might be due to the higher resolution (i.e., detail quality) of the information provided, but not the fundamental characteristics that differentiate KP from KR (i.e., process vs. product/outcome information).

In Cirstea and Levin's study, synchronous KP was provided with task performance, whereas KR was delivered asynchronously with the task. Such study designs might also cause serious issues in making inferences on experiment results. First, the amount of feedback cannot be easily controlled if it is delivered in real-time or at the termination of task performance. For example, if KR is presented asynchronously with task performance, should the presentation duration be the same length as the task performance duration during which KP is delivered? Second, feedback provided during a task might influence performance due to divided attention issues. How information overloading influences learning has not yet been

fully studied. In fact, previous studies have already found that synchronization of feedback can have different effects on skill acquisition and motor learning (see Armstrong's, 1970b paper comparing concurrent KP with terminal KP). Therefore, synchronization of feedback should be controlled in future motor learning experiments, especially in studies comparing KP with KR.

Feedback modalities were also not controlled in Cirstea and Levin's experiment. KP was presented in a spatial visual format, whereas KR was presented in a verbal format. Cirstea and Levin failed to provide a literary basis for their choices of feedback modalities. Their choices might have been based on the fact that kinematic feedback, especially limb position and joint angle information, could most easily be presented through the visual modality. Verbal KR was picked to reduce the information load on the visual modality. It is suspected that these choices were also based on the assumption that feedback modalities have little or no mediating effects on motor skill acquisition or long-term learning. This also assumes that human motor adaptation is a multisensory, highly flexible process whose efficiency does not depend on the effectiveness of a sensory channel for conveying error or performance signals (Sarlegna, Gauthier, & Blouin, 2007).

Even if the above assumptions were true, there might be additional motivational effects when training with feedback provided via different sensory modalities. For example, one feels more motivated when playing video games using force-feedback enabled joysticks. Such motivational effects might influence motor learning and skill acquisition in the long run.

Some studies have not strictly observed the key differences in characteristics between KP and KR in defining experimental conditions. For example, in Kernodle and Carlton's (1992) study, one condition of information feedback was presented in the form of KP with error-correcting cues. Their conclusion was that this type of KP can lead to significant gains in skill acquisition. However, they failed to recognize that KP with error-correcting cues was not KP at all. Instead, they were actually manipulating a combination of KR and KP, which was better than KR alone. In general, researchers should not add additional cues to feedback conditions if their primary goal is to make comparison between KP and KR. KR should be manipulated to reflect movement outcome, whereas KP should be focused on process-oriented information (i.e., information on the state of movements).

Consequently, there is a need for research to control these feedback design parameters and to further study how KP and KR influence motor learning and skill retention. It was posited earlier that the key differences between the two feedback types are related to how they direct trainee attention. KR directs trainee attention to the task goal state, whereas KP directs trainee attention to limb movement state. By comparing the effects of KP and KR on motor learning, a study actually investigates how human attention resources should be allocated during skill training to support learning and retention. This kind of research could also help resolve the basic question of whether motor skill learning is more outcome vs. process oriented.

In the following section, a model of human information processing (HIP) is reviewed and discussion is provided on how motor skill learning occurs. The model is used to explain why KP led to better motor learning and retention than KR in previous studies. Some other

perspectives regarding this research finding (i.e., KP supports more learning than KR) are also discussed. A set of research hypotheses is described at the end of the section.

2.1.5. Why KP maybe better than KR for skill retention: A HIP perspective

In order to investigate performance and learning effects of different information feedback types, there is a need to understand the learning process from a human information processing (HIP) perspective. Wicken and Hollands (1999) described several critical stages of information processing involved in human performance or skill acquisition (see Figure 4). For example, information from various stimulus modalities first enters the short term sensory store (STSS). The STSS permits environmental information to be preserved temporarily and dealt with later. However, no attentional resources are allocated in this process and information stored in the STSS decays quickly. The rate of decay depends on the sensory modality of the stimuli. In general, iconic stimuli have been found to decay much faster than echoic or kinesthetic stimuli in the STSS (Wickens & Hollands, 1999).

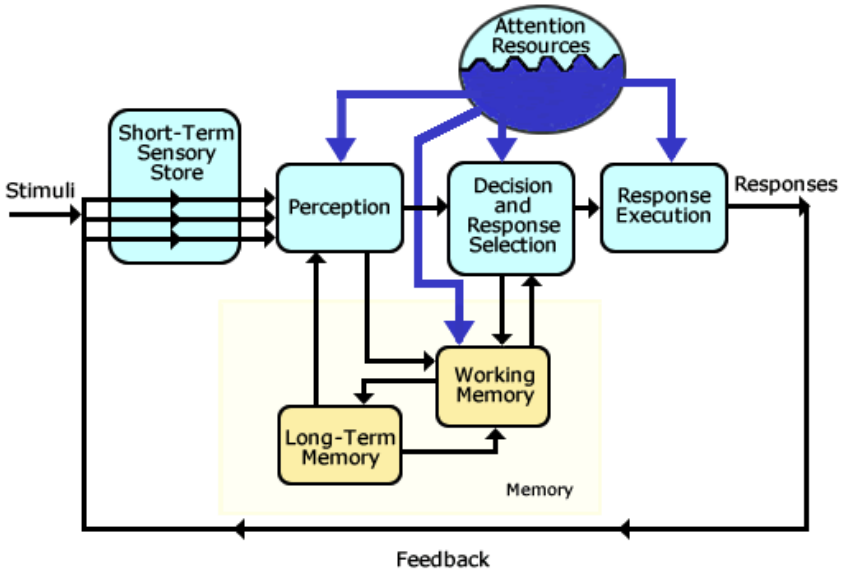

Figure 4. Human information processing model from Wickens (1999)

The processor following the STSS is "*Perception*". Here, information is perceptually encoded using attentional resource allocation. At a basic level, perception can be a single dimension task in terms of detection or miss-detection. At a greater level of complexity, it might also require recognition of multidimensional cues, which would allow for identification of the state of the environment, task and system. For both levels of "*perception*", information in the STSS contacts long-term memory (LTM) stores and is encoded in working memory (WM). More specifically, humans will store the information from environmental stimuli in WM, encode the information as a set of declarative knowledge that is related to the task goal, and further make comparisons with operational rules stored in LTM (e.g., if an object's shape is round with no corners, it probably is a circle or globe). If the task is new and no operating rules exist, new procedural knowledge of the task will be formulated. WM is identified as the key store in HIP affecting skill learning and retention. This is because perceived information is communicated to the memory store so frequently that the development of LTM knowledge (i.e., motor programs or motor schemas) for a new task cannot be achieved without it.

After stimuli are perceptually categorized, a conscious decision is made on what to do with it. This process includes direct selection of a movement response, or it might include decisions to store information in WM or LTM for further rehearsal. The last process is to recall a memory of a motor program and execute the movement. In Wicken's model, humans are considered to be closed-loop information processors. Therefore, a feedback loop exists to modify future control actions based on perception of outcomes of current actions. Furthermore, Wicken's model also assumes that each stage of the process performs

transformation of the data and demands some time for its operation. This suggests that human performance is largely dependent on how smooth the information can be transformed among each processing store, and how much time it would take to finish the entire feedback loop.

Based on the above discussion, it could be argued that skill performance and skill learning are related to different aspects of HIP. Human performance mainly depends on the flow of HIP as a whole, whereas skill learning is more related to the formation of LTMs and how frequently communications occur among the perceptual process, WM and LTM. Performance can be facilitated if the flow of information becomes smooth (rapid in speed and consistent). However, it does not necessarily mean that such skill level can be sustained or persist after experimental intervention is removed. On the other hand, learning can be facilitated if subjects form a mental model (or motor program) for the task more quickly and such model has utility in other tasks that require similar motor skills.

When trainees receive KP feedback during motor skill training, they typically receive raw information with respect to their movement kinematics or kinetics. When this information enters the WM store, trainees need to make comparison of input stimuli with the task goal template. In a reaching task, for example, trainees need to store the current limb position as well as the target position. They also need to conduct mental calculations on the deviation between the two in a three-dimensional (3D) space. After that, the calculated deviation is stored in WM and it is used for decision making and response execution. Such a process requires many interactions between stimuli input, WM, and LTM, which takes time and slows the HIP flow.

Trainees receiving KR, on the other hand, can process information much more quickly without additional internal communications. KR is packaged or pre-coded information on movement outcomes (e.g., you are off the target by 3 inches to your right). When KR enters the perceptual processor, it passes directly to WM and is ready to be used for decision making. Time is saved in HIP and this supports performance. However, learning might be compromised since less structured internal motor memory is formulated for the task. Therefore, although KR might be good for performance acquisition, KP is expected to be better than KR in terms of skill retention and learning.

With respect to motor rehabilitation, KP may also be superior to KR in the sense that it focuses more on improving recovery by addressing movement quality (Subramanian, Massie, Malcolm & Levin, 2010). By using KP, therapists can also easily determine if improved motor capabilities are due to recovery or patient compensatory movements. These findings taken together with the discussion in the previous sections leads to the first hypothesis of the present research:

H1: Augmented feedback on movement state (i.e., KP) was expected to result in better learning than feedback on movement outcome (i.e., KR).

2.2. Feedback types and human motivation

Augmented feedback, in general, is effective for sustaining human motivation during motor learning and rehabilitation. Motivation itself is also regarded as a key determinant of rehabilitation outcomes (Maclean, Pound, Wolfe & Rudd, 2000). Highly motivated patients might work harder and persist longer at a training task, and consequently, improve more as compared with less-motivated patients. Therefore, it seems that the effects of augmented

feedback on motor learning and recovery are mediated by human motivation state. Study of the relationship between feedback and motor learning would not be complete without a thorough review of basic motivation theory.

In the following sections, the concepts of human motivation in the rehabilitation and psychological literature are reviewed. In general, motivation is classified as either intrinsic or extrinsic motivation. After this, there is discussion of the motivational effects of KR and KP. A hypothesis on the relative motivational utility of KP and KR is also presented at the end of this chapter.

2.2.1. Concept of human motivation

Maclean and Pound (2000) provided a detailed review of the concept of patient motivation in the literature on physical rehabilitation and further identified three motivation groups. The first group (based on clinical studies) conceptualizes motivation as a purely internal quality or an aspect of individual personality. These studies place the major responsibility for motor recovery on patients themselves. The disadvantage of such a conceptualization is that moral blame is placed against a patient if recovery is incomplete. The second group believes that patient motivation is affected by social factors including the quality of the rehabilitation staff, patient support networks, and clear goal setting for training. Fostering all these social factors during rehabilitation might lead to the problem of over protection, which is usually associated with low motivation. Therefore, an approach combining internal and social factors in conceptualizing motivation is regarded as helpful.

A more recent study viewed motivation as a hierarchical construct encompassing both energy for and direction of behavior (Elliot, 2006). The first essential element in this model

is a cognitive representation of a future objective that one is to approach or avoid (also known as a *goal*). The *goal* sits in the center of the model and serves as both a directional function for movements and a proximal predictor of behavior. Goals themselves are not sufficient to account for motivated behavior. *Motivations* underlie goals and vary in form and source (e.g., motives and temperaments) as required, and function as energizers of approach or avoidance behavior. In Elliot's view, the distinction between approach and avoidance motivation is fundamental to this model. Approach motivation promotes new positive situations and maintains existing positive situations. Avoidance motivation, on the other hand, focuses on preventing new negative situations and escaping from existing negative situations. Positive/negative valence is the core evaluative dimension of approach-avoidance motivation. Both types of motivation can either be activated by physical stimuli or internally-generated representations of events.

2.2.2. Intrinsic and extrinsic motivations

As previously mentioned, motivation can be further classified into either intrinsic or extrinsic motivation (Ryan & Deci, 2000). Intrinsically motivated activity (or cues) provides satisfaction of innate psychological needs rather than some task outcome. Several fundamental human psychological needs have been proposed and regarded as key determinants for intrinsic motivation (Deci & Ryan, 1985), including a sense of autonomy and competence when performing the task, as well as a sense of relatedness or connections to other human beings and social environments (also known as self-determination theory). The authors further suggested that events or feedback that conduce toward feelings of competence should be accompanied with a sense of autonomy to enhance intrinsic motivation. With

respect to physical rehabilitation, this can be easily achieved by robot-aided therapy with augmented feedback. Additional VR technology can be used to create a virtual team rehabilitation environment to facilitate a further sense of relatedness or connection with others in task performance.

Humans are extrinsically motivated to conduct an activity in order to attain outcomes (e.g., reward and grades) (Ryan & Deci, 2000). Extrinsically motivated activity usually lacks fun and needs external regulations to sustain participation. For example, many of the educational exams prescribed in schools are not intrinsically interesting. Like intrinsic motivation, extrinsic motivation can vary greatly in terms of autonomy by fostering internalization and integration of values and behavioral regulations. For example, *external regulation* can be regarded as the least autonomous form of motivation, through which actions are conducted to obtain rewards or avoid punishments. *Introspection* is a more self-determined type of motivation and it represents regulation of actions to avoid guilt or to attain ego-enhancement. A person performing an act to enhance or maintain self-esteem and feeling of worth is a form of *introspective* motivation. An even higher autonomous form of extrinsic motivation is regulation through *identification*. In this case, a human begins to consciously value an activity and identifies it as relevant to one's life goal. If a person can fully transform regulations into their lifestyle or make regulations consistent with one's needs and values, this leads to the highest autonomous form of extrinsic motivation referred to as *integrated regulation*. The authors argued that extrinsic regulations or external goals are less efficient and powerful motivators than intrinsic motivation. In some cases, they might disrupt behavior that is intrinsically motivated (e.g., external goals conflicting with internal

interests). Therefore, the process of internalization and integration is important for external goals (or event cues) and such a process can be facilitated by the desire for autonomy, relatedness and competence.

2.2.3. The motivating effects of KP and KR

KP and KR are augmented extrinsic cues that can support intrinsic motivation if well designed in motor learning. Presentation of movement patterns (i.e., KP) to subjects during performance can make training tasks more entertaining and interesting, which indirectly affects intrinsic motivation. For example, in the Colombo et al. (2007) experiment, subjects were instructed to practice robot-aided elbow flexion and extension movements in a video tracking game scenario. KP was provided in real time indicating both the task target position (i.e., a red circle) and the current position of the control handle (i.e., a green circle). Subject self reports of motivational states were collected using the standard Intrinsic Motivation Inventory (IMI) questionnaire (McAuley, 1989; Plant & Ryan, 1985). Results revealed the feedback group to produce higher IMI scores for interest, usefulness and importance subscales and lower values for tension and pain subscales, as compared to a control group. These findings indicated enhanced intrinsic motivation states for the feedback group. However, they found minimal or even no correlation between behavioral responses and self-reported motivational variables. This correlation result was consistent with previous findings (Ryan, Koestner & Deci, 1991). Taken together, the results suggested that self-report questionnaires might be sensitive enough to reveal small changes (probably improvements) in motor outcomes and learning.

Motivational effects of KR have been found to be a function of goals and knowledge performance relative to criteria (Locke, Cartledge & Koeppel, 1968). When providing subjects with information regarding task (or movement) outcomes, the feedback content is usually related to explicit or implicit aspects of the task goal. Considering the KR of an exam score, explicit goal information might be the standard of obtaining a "B", whereas implicit goal information might be "*obtaining a score higher than the previous one*". Any discrepancy between the KR and desired goal states causes motivational effects. Locke et al. argued KR is effective in motivating performance largely due to its relation to goal criteria and performance. There is no additional effect of KR if it is separated from goal setting. This argument is particularly related to, and consistent with, Elliot's (2006) hierarchical theory of motivation, which places "*goals*" as a directional indicator for proximal behavior.

The goal-outcome comparison mechanism of extrinsic KR can further facilitate internalization and integration of external regulations (or activities) and make them more intrinsically motivating and entertaining. For example, a student knowing his exam score is far above the class average would feel a sense of self-esteem and ego-enhancement. Such experiences would further result in internalization of external regulations (e.g., following exam procedures) and may make boring academic activities more automatic and self-motivating. Recent studies even show that mild negative KR feedback can increase intrinsic motivation if it is associated with cues signaling self-determination (Anderson & Rodin, 2006). In Anderson and Rodin's study, a subject task was to answer a set of brain-teasers with either negative (i.e., "*6 out of 10 correct*") or positive feedback (i.e, "*9 out of 10 correct*"). The perception of self-determination was controlled through subject instruction by

manipulating whether or not the subject had: (1) a choice of the questions to solve; (2) an expectation of evaluation; and (3) a sense of public self-consciousness of the score. Results revealed that KR (either negative or positive) facilitated intrinsic motivation if associated with environmental cues supporting self-determination.

In general, the above reviews suggest that both KP and KR have utility in motivating activity and learning. However, their underlying motivating mechanisms are quite different. KP presents movement patterns or processes to subjects (e.g., using an avatar) and this might be helpful for entertainment purposes. If KP is not associated with an explicit definition of a goal (e.g., raise the avatar forearm to 45 degrees), such motivating effects might not last long in terms of performance and learning. For example, people will eventually become bored if they keep watching a 3D avatar skeleton repetitively performing the same task during training. KR, on the other hand, is commonly associated with an implicit or explicit goal, and its goal-outcome comparison mechanism facilities the process of self-determination, which directly enhances intrinsic motivation. Such processes last longer and could be regarded as a stronger form of motivation. Therefore, our second hypothesis is as follows:

H2: KP and KR, in general, were expected to motivate rehabilitation performance. KR serves as a corrective function and was, therefore, expected to lead to enhanced and longer intrinsic motivation than KP.

CHAPTER 3: FEEDBACK MODALITY, MOTOR LEARNING AND MOTIVATION

The common receptors for feedback supplied to the closed loop HIP system during motor learning and rehabilitation are the eyes, ears and skin. These sources provide valuable input to the central nervous system with different utilities for movement learning and motivation. This section begins with a discussion of sensory characteristics and their relationship to motor control and learning. Some empirical studies comparing the effects of feedback modalities on motor skill learning and rehabilitation training (in specific) are then reviewed. A set of hypotheses on sensory modality effects on skill learning and retention is presented at the end of the chapter.

3.1. Sensory characteristics and motor learning

The eye is the most critical receptor supplying information about movements of objects in the outside world. Visual information is used when the auditory system is taxed by environmental noise or in situations when messages via other modalities are too long and complicated to encode and retain in WM. For example, there is an advantage to using visual presentation if a message deals with object locations in space (e.g., limb position in space) (Deatherage, 1972). A disadvantage of visual feedback is that there may be too much information on the display and this can cause visual tunneling. In such situations, operators may look at the display, but they do not process all information effectively due to clutter. This situation occurs with higher frequency for persons with central nervous system compromise. They may have more difficulty in processing information than the normal population. Therefore, how to effectively translate information to optimize human perception

and facilitate visual feedback during motor learning and rehabilitation is a research area that needs to be investigated in the future.

Previous research has found that beneficial effects of visual feedback on motor control cannot be achieved for rapid movements. For example, Woodworth (1899) asked subjects to perform back and forth movements with a pen with the goal that each movement be equal in length. Visual feedback was provided to indicate aiming errors. Subjects were separated into either an eye-closed condition or an eye-open condition. His results showed that significant reductions in error occurred in the eye-open condition only when movement duration was longer than 250 ms. A more recent study (Zelaznik, Hawkins & Kisselburgh, 1983) trained subjects to move a stylus to a small target about 15 cm away from a starting position. In their study, they turned off a light in the test environment in a predictable manner. Their results showed significant differences in errors only when movement time was longer than 150 ms. This suggested that vision, when its presence can be expected, can be used in far less time than suggested by Woodworth. This might due to iconic stimuli decaying rather quickly in the STSS (usually less than 1 second) and limiting further processing in LTM during rapid movements.

Feedback through auditory and tactile modalities provides additional sources of information when the visual system is overloaded. Such cues are good for presenting warnings and announcing time related events. They are superior to visual feedback in the sense that they can also be delivered when subjects are in motion (Deathridge, 1972). In addition to this, semantic coding is also possible through audio or tactile signals. For example, the pitch of a warning tone can be used to indicate the amount of error in a

movement; the frequency of vibration could be indicative of the position of a hand (relative to a target). The particular time constant of decay is also a bit longer for the short-term auditory store and short term kinesthetic store (2 to 8 seconds), as compared with short term visual store. This could have a strong exteroceptive role in motor learning for seniors or neurologically impaired patients, since they simply need more time to process information, especially during rapid movements. The disadvantage of using auditory or haptic feedback is that the content of any message must be limited due to the transient nature of the displays. Complex information, such as limb position over time, might not be coded effectively in these modalities.

3.1.1. Visual feedback and motor learning

Visual feedback has been used to present *spatial* error information in robotic-assisted rehabilitation (Brewer, Klatzky & Matsuoka, 2008; Wei, Bajaj, Scheidt & Patton, 2005). Wei et al. (2005) presented several types of spatial error information to 16 subjects via the visual modality. The subjects were instructed to make reaching movements with constant speed with a robotic manipulator. The visual feedback consisted of current hand position and target position (i.e., visual KP), as well as a trajectory connecting the two objects indicating instantaneous *error* (i.e, visual KR). Subject vision of the arm was obscured by a projection plane on which the artificial visual feedback was projected. Results revealed that all types of error feedback led to an improved level of learning though the visual modality.

In another related study, Brewer et al. (2008) mapped the force a subject applied during training to a visual feedback bar (i.e., a shaded part of a vertical bar indicated the level of force applied). In this way, they transformed non-spatial force information into spatial

directional information, which was more appropriately presented via the visual modality. Promising results were found when evaluating such a feedback paradigm in clinical tests with a TBI patient and a stroke patient. However, no comparisons between such translated visual feedback and direct force feedback were made.

3.1.2. Auditory feedback and motor learning

Auditory feedback can also be used to represent error or performance information during motor learning. For example, Maulucci and Eckhouse (2001) investigated how real-time auditory feedback might enhance motor recovery of patients in the chronic stroke period by means of upper extremity trajectory modification. Sixteen patients (8 in a feedback group and 8 in a practice group) were recruited to make reaching movements to three targets. A normal path region for the hand sensor was first established as a threshold in the feedback group. No auditory tone was presented if a patient's hand was within the "normal" region. Otherwise, a tone was emitted as an indication of the occurrence of error. The frequency of the tone increased as the error magnitude increased. In both the feedback group and practice (i.e., no feedback) group, a light was activated to indicate which target to hit. The light was extinguished when the target was hit (i.e., visual KR). Results showed that modification of the reach trajectory could be accomplished either with practice alone or through practice accompanied by auditory feedback. However, improved path performance required auditory feedback training. These results also suggested that feedback delivered via the auditory modality was good for motor outcomes and learning. However, the relative benefit between the feedback modalities was not investigated.

Related to this, Johanna et al. (2009) further investigated the effect of simple or spatial auditory feedback on the kinematics of reaching movements in hemi-paretic stroke patients. In the simple feedback condition, information regarding hand-target distance was provided. More specifically, the volume of the auditory cue increased as the hand approached the target. In the spatial feedback condition, information was provided regarding the direction of the target relative to the hand. For example, the intensity and frequency of the sound in the left ear would increase if a patient's hand approached the right side of the target. A control group with no feedback was also included. Results showed that additional auditory feedback improved movement smoothness only in patients with right hemisphere damage, probably due to hemispheric specialization (e.g., limb kinematics are mainly controlled in the right hemisphere using closed-loop control, whereas the left hemisphere focuses more on the control of limb dynamics). No differences between the two types of auditory feedback were found.

In another study, Nichols (1997) described a balance training system that provided performance (and error) feedback to patients in real time through both visual and auditory modalities. For example, the weight on the feet of a patient was first determined using force plates; the force data were then transmitted to a computer on which a cursor was used to visualize the current center of force (i.e., visual KP). The subject was instructed to maintain the cursor in the center of the screen as marked by a cross-hair during training. In addition to this, the percentage of weight on each foot was also presented visually on the screen (i.e., visual KP). If less than a target weight was placed on the paretic limb, an auditory tone was emitted as an indication of KR. Evidence favoring such balance retraining protocols was

found and discussed. However, no direct comparisons were made between visual feedback and auditory feedback.

3.1.3. Haptic (force) feedback and motor learning

Haptic feedback has also been used to represent performance and error information during training. For example, Morris et al. (2007) explored the use of haptic feedback to teach an abstract motor skill that required recalling a sequence of forces (e.g., surgery or tattooing tasks). In their experiment, participants were guided along a trajectory and were asked to learn a sequence of one dimensional forces via three training paradigms. Subjects could see a target trajectory and the current cursor position via a visual interface in all training conditions. In the haptic condition, a haptic device applied the opposite of the imbedded force pattern to a subject's hand (i.e., haptic KP). Subjects were instructed to apply a force to keep the device in the normal plane. In the visual only feedback condition, however, no haptic representation of the target force patterns existed. Instead, a blue bar was superimposed on the cursor to indicate the instantaneous target force pattern. In the visuo-haptic condition, the haptic feedback and the visual feedback were combined. An additional green bar indicating the current force applied by the subject was also added. Results showed that the visuo-haptic condition led to significantly less force recall error than the visual feedback condition. The visual feedback condition led to significantly less error than the haptic feedback condition. Results suggested that the combination of feedback modalities might be beneficial for enhancing motor learning and recall versus feedback delivered via a single modality.

Another related study (Adams, Gopher & Lintern, 1975) investigated the effects of visual and proprioceptive feedback on learning and performance in a self-paced linear positioning task. Subjects were instructed to displace a slide along a linear track with the criterion movement of 20.3 cm. There was also a scale on the track (hidden from the subjects) that could be used to calculate movement error after each trial. In the visual feedback condition, subjects could see the apparatus and their hand while they moved the slide through a one-way mirror (visual KP). In the force-feedback condition, a subject's hand and the apparatus were obscured; however, a spring was attached to the slide post so that the subjects could mentally "*calculate*" the distance according to the force applied (force KP). In general, results showed that visual KP was more effective than hatpic KP in terms of error reduction in such a positioning task. This was consistent with the view that visual cues could be better used by humans in spatially dominant tasks.

Akamatsu et al. (1995) compared tactile, auditory, and visual feedback in a pointing and selection task using a mouse-type device. In the auditory feedback condition, a 2 kHz tone was emitted while the cursor was inside the target (auditory KP). In the visual feedback condition, KP was delivered through a change in target color when the cursor was over the target. In the tactical condition, subjects felt a tactile stimulus to the fingers (by special transmitters attached to the mouse) when the cursor was over the target. This study also evaluated a control condition with no feedback and a combined feedback condition (all the cues). No differences were found in overall response times. However, significant differences were found in the final positioning times (from the cursor entering the target to selection of the target). Tactile feedback turned out to be the quickest among the three conditions. This

result suggested subjects could make corrective responses almost at the same time after KP was delivered through different sensory modalities. Therefore, motor skill acquisition and performance based on KP should be comparable though visual, auditory and tactical mediums. This is consistent with the view that motor adaptation is a multisensory, highly flexible process whose efficiency does not depend on the sensory channel conveying the error signal (Girardi, McIntosh, Michel, Vallar & Rossetti, 2004). However, no retention periods were included in the prior research to assess the effects of the KP modality on skill learning.

3.2. Feedback modality and motor skill learning

In summary, few studies have been conducted thus far that have investigated the relative benefits of visual, auditory and tactile feedback in the area of motor skill learning. Specifically, we still do not know which modality is most suitable for KP (or KR) in terms of motor learning and retention. The above reviews also suggest that the choice of feedback modality might be task dependent (e.g., the visual modality is good for spatial tasks; the auditory modality is good for temporal tasks; tactical cues are good for tasks involving force learning [Huang, et al., 2005]). The majority of fine motor rehabilitation tasks involve repetitive hand-eye coordination, indicating that these tasks are more visually dominated. This provides possible explanations for the previous findings suggesting visual cues were more effective than haptic cues in terms of motor outcomes (Adams, et al., 1975; Morris, et al., 2007).

For example, since KP is associated with the nature of movement patterns (usually spatial), it is commonly presented via the visual modality (e.g., limb position over time). This

could be the easiest and quickest way for the learners to comprehend the information and further make changes in subsequent trials. Recent studies (see above review), however, attempted to use auditory spatial coding or dynamic force-feedback to represent KP. This required additional coding rules to be stored by trainees. For example, learners need to remember the panning of a sound is indicative of the position of the limb. This added more processing steps (*detection*, *recognition*, *identification*, *association*, and *categorization* etc.) during communication between WM and LTM, which might further affect the effectiveness of processing KP and performance outcomes.

However, the above discussion does not necessarily suggest the visual modality is best for KP or KR in terms of motor learning and retention. In fact, few studies have been conducted involving a retention period to investigate feedback modality effects on long term motor learning. If feedback cues can be effectively and equivalently conveyed in visual, auditory or kinesthetic channels, the key differences among them would be the duration of cue retention in the STSS and the length of associated HIP. Kinesthetic cues can be retained longer than auditory cues, which in turn are sustained longer than visual cues in the STSS. Cowan (1998) reported that information entering the STSS could be retained up to 8 seconds for iconic cues, and 20 seconds for auditory and kinesthetic cues. Such differences are expected to lead to differences in motor memory generation, which is regarded as a key component for facilitating motor learning. In other words, the pattern of desired muscular innervations may be stored centrally in LTM more effectively if cues are retained longer in the HIP loop.

In the present study, it is assumed that humans are active information processors in the sense that they will process information as long as the information and attentional resources are both available. On this basis, learning outcomes were expected to be greatest for modality cues (in decreasing order) from haptic to auditory to visual (H3).

3.3. Feedback modality and motivation

Feedback modality also has utility for affecting human motivation during skill training periods. For example, Colombo et al. (2007) posited that presenting visual cues in a robot-assisted tracking task would be good for motivational purposes. Loureiro et al. (2001) also found that the use of haptic feedback in robot-assisted stroke rehabilitation increased patient attention and motivation responses. Even the simplest haptic stimulation has been found to provide emotional or motivational information (Salminen, et al., 2008). Wickens and Hollands (1999) also suggested that auditory or haptic cues were better for warnings or motivating indicators, if the visual channel was taxed. Streams of auditory or hapitc information can remain in the pre-attentive STSS for much longer periods than visual information, rendering them stronger or more effective as motivational variables. These studies provide a basis for the present experimental design in which task motivation levels will be manipulated through changes in both feedback type and feedback modality.

3.3.1. Feedback modality and human motivation

In one study, Szalma et al. (2004) investigated how different sensory modalities affected human stress and motivation responses in a vigilance task. In one condition, subjects viewed a repetitive presentation of a horizontally-oriented white bar against a gray background on a

display (i.e., visual cues) and made responses. In another condition, subjects listened to 247.5 ms bursts of white noise (i.e., auditory cues) from headphones and made responses. They found that sensory modality had significant effects for human motivation. Subjects in the visual condition reported being less motivated and less happy than those in the auditory condition. This suggested the sensory modality of signals is a matter of significance when a task requires vigilance and continuous attention (e.g., a Fitts' task).

There is also evidence that the sense of touch can lead to higher motivation or emotional responses than visual and auditory cues. Lecuyer et al. (2002) investigated the effects of visual, auditory and haptic cues on performance of an industrial insertion task (i.e, inserting a ball through five apertures) in a VR environment. They also collected subjective ratings of pleasantness and perceived choice of feedback types. Perceived pleasantness was positively related to emotional valence, whereas perceived choice was also theorized to be a positive predictor of both self-report and behavioral measures of intrinsic motivation (Deci & Ryan, 1985). Results showed that haptic cues were considered more pleasant than the other cues. Subjects were also more willing to choose training with haptic cues than with visual or auditory cues. These findings suggest that hapitc cues may lead to higher emotion or motivational responses than visual or auditory cues.

3.3.2. Motivational effects of feedback modality and type

Based on the above reviews, it is hypothesized that feedback modalities would also influence human motivation level. In specific, haptic cues were expected to be more motivating than auditory cues, which, in turn, were expected to be more motivating than visual cues. However, sensory modality was also expected to be less motivating than feedback content

(i.e., KP or KR). This is due to the content of feedback directly relating to human intrinsic motivation (Deci & Ryan, 1985; Ryan & Deci, 2000). In a framework by Deci and Ryan, they stated that human intrinsic motivation could be enhanced by manipulating cues that facilitate introspections (i.e., ego involvement of the task) and identification (i.e., awareness of the importance of a behavior). KR was expected to be more motivating than KP since its performance–goal comparison mechanisms contribute to both of these processes. Although feedback modalities have motivating effects, they do not affect motivational processes directly. Therefore, the hypothesized motivation levels for feedback conditions are as follows:

Table 2. Hypothesized motivation level for feedback conditions (H4)

ID	Feedback	Motivation level
1	No feedback control	Least motivating
2	Visual KP	
3	Auditory KP	
4	Haptic KP	
5	Visual KR	
6	Auditory KR	
7	Haptic KR	Highly motivating

3.4. Human motivation and motor learning

3.4.1. Physiological arousal as indicators of human motivation

Motivation is closely related to the concepts of emotional arousal and valence. According to the dimensional theory of emotion (Russell, 1980), all emotions can be defined in a two-dimensional space, with axes of affective arousal and valence. Valence can be conceptualized as the intrinsic attractiveness (positive valence) or aversiveness (negative valence) of an event, object, or situation (Frijda, 1986), whereas arousal serves as an energizing force that activates and strengthens potential action (e.g., approach or withdraw). In addition to this,

two major motivational systems exist in the human brain including appetitive and aversive systems (Dickinson & Dearing, 1979). Appetitive and aversive systems are prototypically expressed through behavioral approach and behavioral escape, respectively. In this sense, they account for the primacy of the valence dimension (Lang, 1995). Arousal reflects to a greater extent variations in the activation of the two systems. This suggests that valence could be used to indicate motivational direction in terms of executing either approach or avoidance movements. Arousal measurements could be used to indicate motivational magnitude.

Similar to motivation, emotions in terms of arousal and valence are fundamentally associated with behavioral action (M. M. Bradley, 2000). However, sequences of events triggering emotion and subsequent behaviors can vary greatly depending on the particular theory. For example, early researchers argued that emotion was the result of bodily changes (e.g., one feels fear after heart rate increases [Lange & James, 1922]), whereas others regarded the expression of emotion as simultaneous with activation of the body, not the result of it (e.g., one feels fear and, at the same time, one's heart rate increases). More comprehensive views contend that both physiological arousal and a cognitive label are necessary for the full experience of emotion (e.g., a new born baby would not feel fear at a snarling dog because there is no such cognitive experience connecting the emotional fear with the input cue [Schachte & Singer, 1962]). If a physiological state is aroused and we have no ready explanation, humans will search for environment cues. Under either theoretical hypothesis, emotions can serve as motivators for further action (Petri & Govern, 1991).

Therefore, human motivation state can be inferred through the measure of emotional arousal and valence, both of which can be quantified and collected either through self-appraisal measures, such as the Self-Assessment Manikin questionnaire (SAM) (M. Bradley & Lang, 1994), or through monitoring of physiological responses (Larsen & Fredrickson, 1999). For example, previous studies have found that heart rate (HR) is positively correlated with emotional valence (M. Bradley, Greenwald & Hamm, 1993) and arousal (Mandryk & Atkins, 2007). Galvanic skin conductance (GSR) has also been found to increase as the level of arousal increases (Amershi, Conati & McLaren, 2006; Mandryk & Atkins, 2007). No consistent relationship between GSR and valence has been found.

3.4.2. Relation of motivation and motor learning

Based on the literature review in the preceding sections, it seems that KR, although associated with higher motivational (or arousal) state than KP, has been expected to lead to less motor learning. This suggests that arousal can be both beneficial and detrimental to long term performance retention and skill learning (see Table 3). However, if we only look at the relationship between KP and the no feedback condition in Table 3, human motivation level seems to be positively related with performance retention. This contradictory expectation suggests that the effects of human motivation level on motor learning might not be linear and needs to be further investigated.

Table 3. Detailed hypothesis

Responses	Hypothesis
Long term learning and retention	KP > KR > no feedback
Motivation level	KR > KP > no feedback

Note: "A > B" means that A is better than B in terms of the response variables specified in the left column

Previous arousal studies also shed some light on this inference. For example, Yerkes-Dodson (1908) proposed a non-linear inverted "U"-shaped relationship between arousal and performance. In a high arousal state, humans tend to attend to only important objects (or cues) with the result that peripheral information remains unattended (Easterbrook, 1959; Heuer & Reisberg, 1990). This can lead to degraded performance. In a low arousal state, humans tend to get bored and pay little attention to the task at hand, which also compromises performance. Kluger and Denici (1996) argued that feedback-induced attention to learning processes does not guarantee an improvement in performance. A slightly above average level of arousal is considered better for motor task learning (Martens, 1974). In one study, subjects performed a series of precision motor tasks under either a high arousal state or baseline arousal state (Noteboom, Fleshner & Enoka, 2001). The high arousal state was achieved though either having the subjects mentally perform several math problems during tasks, or physiologically providing an electric stimulus to a subject's left hand. Results showed that both stimuli lead to significant increases in arousal compared with the baseline conditions. Task performance (i.e., steadiness) was significantly worse in the math aroused condition. No differences in terms of performance were found between the shock aroused condition and baseline condition. These results suggested that cognitive arousal states might compromise physical task performance, and such decrements are even worse than in low-arousal states.

In another related study, Noteboom et al. (2001) further examined the steadiness of precision gripping task performance in the absence and presence of an electrical stimulus stressor on subjects with various levels of trait anxiety. Trait anxiety was measured with the State-Trait Anxiety Index (Spielberger, 1985) to indicate a subject's average level of anxiety.

Subjects with extreme test scores (i.e., low anxiety or moderate anxiety) were selected and assigned to one of the three testing conditions: a control group with no electricity stimuli, a low anxiety aroused group, or a moderate anxiety aroused group. Results revealed that subject arousal increased with stressor intensity and was associated with a decrease in gripping performance. Such effects were especially evident for subjects with moderate trait anxiety.

The contradictory hypothesis in Table 3 might be explained by investigating the stress level associated with KP and KR. The feedback-standard comparison mechanism of KR might contribute to additional stress during motor training. For example, an athlete knowing his previous training result would strive to beat that score in a future training session, which would cause additional stress. Such stress also exists when therapists inform patients of a training score and expect them to perform better next time. Recall that "*motivation*" is commonly regarded as an individual trait in clinical settings. Such beliefs further strengthen the stress effects of KR (e.g., *you did not achieve better training results this time due to your own actions*). The resulting high stress level indicates high negative arousal, which has been found to be associated with degraded motor performance (Noteboom, Fleshner et al., 2001).

However, there are several major limitations of the studies reviewed above. First, both studies only focused on how human arousal level influenced instantaneous task performance. No retention periods were included in the studies and, therefore, the effects of arousal or motivation on motor learning cannot be assessed. Second, both experiments used artificial external stimuli (i.e., electricity or mental math calculations) to exert additional

stress on subjects during the task performance. This is more related to human extrinsic motivation manipulations.

In future studies, manipulations of human arousal level should focus more on intrinsic aspects of motivation, that is, designing the task as more intrinsically motivating (or interesting) rather than adding external stressors. This could be achieved by presenting various forms of feedback to subjects through different sensory modalities (e.g., visual and auditory). For example, playing video games using a Wii system with haptic feedback controllers is more motivating than using another system with regular controllers since additional information on task performance is provided. Future research should also focus on studying how human motivation level induced by various forms of feedback during the skill acquisition period might influence skill learning and retention in the long run.

The Yerkes-Dodson law, however, is not an entirely sufficient basis for formulating hypotheses on the relation of motivation and learning since it is a performance-based model and not a learning-based model. Few studies have attempted to apply the model to a skill learning and retention context. Some researchers also criticized the inverted U-shape arousal theory and contended that it was too simplistic or trivial for performance prediction (Neiss, 1988). Others have suggested that the interaction of arousal and HIP style determines task performance (Storbeck & Clore, 2008). There is also evidence suggesting that high positive arousal states might be beneficial for performance (Perkins, Wilson & Kerr, 2001). Although this information is valuable from a research perspective, the goal of the present study was not to evaluate the inverted U-shaped arousal performance relationship (such evaluation can be found in K. Anderson [1990]). Instead, the goal was to attempt to identify a correlation

between subject motivation levels and motor learning, and to investigate how various levels might affect skill retention (through a regression analysis). In general, a non-linear relationship between human motivations and learning level was expected. Low intrinsic motivation could degrade skill retention and learning due to boredom. In this situation, key information related to HIP and LTM formation might be unattended by trainees, which would further compromise learning. High intrinsic motivation levels are also expected to lead to worse learning. Such a relationship is not considered to be attributable to the stress level induced by external stimuli. Instead, it is also related to the issue that highly intrinsically motivated trainees might focus only on specific task information (e.g., interface or task elements that interest them). Some other peripheral interface information, which may be "uninteresting" (habituated) but important for HIP and procedural knowledge formation for the task, might be left unattended. A moderate level of motivation was expected to lead to more learning than low or high motivation levels (see Figure 5). In the present work, a polynomial regression analysis was conducted to test the above hypotheses.

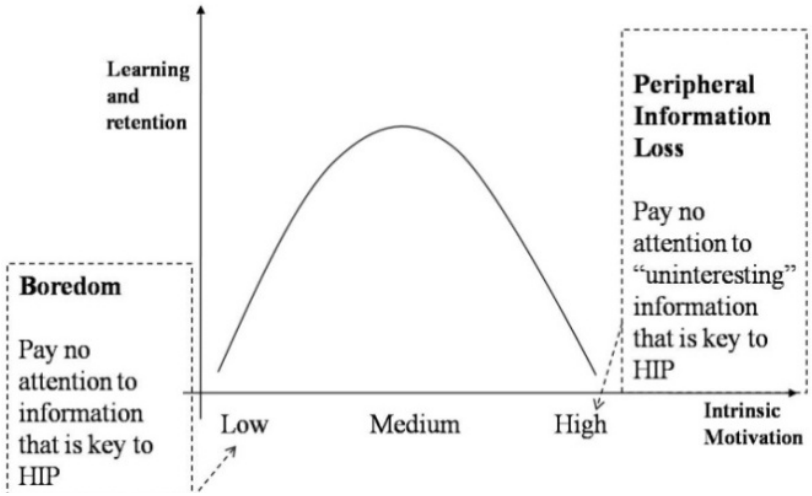

Figure 5. Hypothetical relationship between intrinsic motivation level and learning

3.4.3. Literature review summary and research goal

As a summary, two types of feedback, namely KP and KR, were found to be commonly integrated in training systems in the rehabilitation or industrial skill learning scenarios. Previous studies have attempted to compare the effects of KP and KR on learning outcomes. However, they failed to control the modality through which the feedback was presented. In fact, the above literature review suggests that feedback modalities may indeed affect skill learning and retention. On this basis, a well-known HIP model (i.e., the pipeline model by Wickens) was used to explain how the human learning process might be affected by feedback type and modality.

Second, the investigation of human emotion and motivation is also critical for ensuring positive training experiences. Prior studies suggest that motivational mechanisms differ among the types of feedback. KP is not associated with an explicit task goal, and motivational effects of the feedback are generally not expected to last as long as for KR. Feedback modality might also affect human motivation and emotional responses, but to a lesser extent as compared to feedback type. These expectations were based on Deci and Ryan's Self Determination Theory of human intrinsic motivation.

Third, a nonlinear relationship between human motivation and motor skill learning level was hypothesized based on the literature review. Similar to the relationship between arousal and performance, both high and low motivation were expected to be detrimental to skill learning due to loss of peripheral information and boredom, respectively. The current study collected data on both human motivation and learning level, the relationships of which were quantified using a polynomial regression analysis.

In general, the literature review revealed that there is a lack of empirical research that has investigated how various feedback types and modalities can influence skill learning and human motivation. Such research is critical since it can provide a basis for guidelines on how to redesign existing feedback training systems to support learning and retention. Such guidelines can also be applied to industrial skill training to support learning and save training costs for companies over long-term periods.

To address these research needs, an empirical study was conducted that involved repetitive training of a basic psychomotor task using a complementary haptic device. In the following sections, the detailed experimental protocol is described with specific research hypotheses. Pilot data from three participants was collected and the general results are discussed.

CHAPTER 4: PILOT TEST METHODOLOGY

4.1. Objectives

The objectives of the pilot test were threefold. The first was to prototype a computer-based psychomotor training task using a contemporary haptic interface. The pilot test was expected to be helpful in terms of software testing. The second objective was to assess the effects of feedback type and modality on motor learning and human motivation. This was also the main objective for the full experiment (presented later). Pilot data was used to estimate the total sample size needed for the full experiment in order to reach the desired statistical power for main effect testing. Thirdly, pilot test data was expected to support detailed training task parameter specification (e.g., level of difficulty).

4.2. Participants

Three subjects (2 male, 1 female, average age = 30, SD = 9; all were right handed) from the university population participated in the pilot testing on a voluntary basis. All participants were naive to the nature of the experiment and research objectives. They were required to have normal or corrected 20/20 vision and no hearing impairment or loss. They were also expected to have no prior experience in using a Novint falcon haptic device. In addition to this, they were expected to be able to follow simple instructions on the assigned motor tasks. The experiment involved repetitive elbow-shoulder-wrist movements in an upright, seated posture. Potential participants were excluded from the study if they had current or chronic back, shoulder, neck, or wrist pain.

4.3. Equipment and apparatus

The equipment used in this experiment included one standard HP dv2211 tx laptop, one Novint Falcon haptic device, and two sets of Harman/Kardon speakers. The Java Eclipse IDE (integrated development environment) was used to develop the computer-based training task application, including the feedback test conditions. All subjective response measurements (e.g., the intrinsic motivation inventory) collected during the study were also computerized using Flash applications developed with Actionscript 3.0. Participants were tested individually in a quiet small conference room without disturbances.

The Falcon device allows a subject to interact with a computer by controlling cursor motions in three dimensions with high-fidelity, three degree of freedom (dof) force-feedback. The maximum force output of the device in any direction is up to 2 Newtons. The device works like a mouse for navigating a cursor but in a 3-D space. There are four customizable buttons on the Falcon controller that can provide mouse-like functions such as "*left-click*" and "*right-click*". When a subject holds the Falcon's grip and moves the cursor to interact with a virtual object, servomotors in the device turn on and force-feedback is updated at approximately 1000 Hz to provide sensations of texture, shape, weight, dimension and dynamics. Using the Falcon control, subjects can perform computer-based psychomotor tasks (e.g., a Fitts' game developed for the purpose of this study) in a more realistic way. The control also helps subjects develop real physical skill and motor memory.

4.4. Experimental Tasks

The subjects' task was to continuously perform a series of identical Fitts' tasks in an experimental block. A Fitts' task was selected because it involves fundamental human

motion elements that are similar to those in the physical rehabilitation area or in industrial manual work settings. A Fitts' task also resembles the vigilance task reported in Szalma et al. (2004) in which subjects had to attentively monitor the task and make responses. Each experiment block included 40 individual Fitts' targets, each of which posed the same index of difficulty (ID) level. During the task, a square target appeared at a random location on the screen. The subject's goal was to navigate the cursor to the target (using the Falcon device) and execute a hit on the target. The target remained on the screen for only 1.5 seconds. This duration was selected based on the movement time (MT) estimation using Fitts' law, as presented by Card, English and Burr (1978). Their MT estimate using a regular mouse for the same ID level was approximately 1.37 seconds. Considering that the present experiment used a novel input device, the time estimate was rounded up to 1.5 seconds. This estimate was also tested based on participant feedback during the pilot test. The goal was to ensure a certain level of difficulty for the task, and at the same time, maintain learning feasibility. A new target would appear at another random location on the screen along the same ID circle under three conditions: (1) a correct hit on the target occurred, (2) the subject did not make a click within 1.5 seconds, or (3) the subject clicked at a screen location but missed the target (see Figure 6). The application was terminated automatically after all targets had been presented. Again, the number of targets presented in a trial was arbitrarily selected by the principal investigator and was tested for learning assessment purposes using an iterative approach.

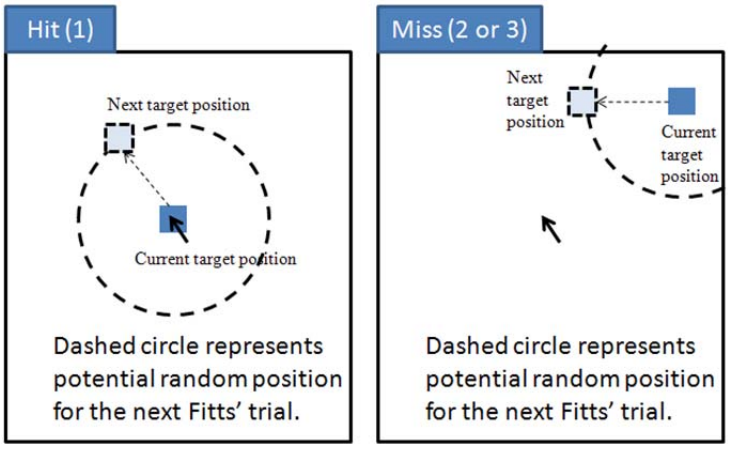

Figure 6. Fitts' task; left indicates situations of hit; right indicates situations of misses.

Subjects were asked to perform the task with their non dominant hand. This approach was used to simulate certain motor control impairments for disabled persons. The approach could also be used to simulate industrial work environments in which operators may not be familiar with a particular assembly task or they may use their non-dominant hand for "pick and placement" of parts and dominant hand for assembly or tool use (e.g., drilling). Previous studies have found that disabled persons not only have motor control problems such as limb coordination and balance, but they also have cognitive impairments in learning, attention and concentration (Barnes, 1999). Such impairment characteristics have also been extensively demonstrated during use of the non-dominant hand in motor skill training.

For example, a recent study revealed asymmetrical manual performance in grip strength and manual dexterity in right-handed subjects (Ozcan, Tulum, Pinar & Baskurt, 2004). In specific, the non dominant hand generates less grip strength and worse hand dexterity as compared with the dominant hand. However, such differences were not found with left-handed subjects, suggesting that right-handed participants might be more suitable

for simulating brain injury patients. Such asymmetric (or degraded) motor skill can be explained not only by decreased use and training of the hand muscles, but also by relatively decreased cortical excitability in the non-dominant motor cortex (Boggio, et al., 2006).

In another related study, Sainburg and Kalakanis (2000) compared the coordination patterns employed for the left and right arms during rapid targeted reaching movements. Results showed that the hand trajectories and joint coordination patterns during the movements were systematically different between the two hands. Inverse dynamic analysis revealed substantial differences in the coordination of muscle and inter-segmental torques for the left and right arms. These findings strongly suggest that distinct neural control mechanisms are employed for dominant and non-dominant arm movements. For example, Caeyenberghs et al. (2009) found that movements of the dominant body side were associated with additional activation of the brain, as compared with the non-dominant side.

The use of the non-dominant hand might also lead to motor memory and planning challenges. Yamashita (2010) found that recall accuracy in the Rey–Osterrieth Complex Figure Test (ROCF; reproduction of a geometrically complex figure by drawing) was significantly lower when the non-dominant (left) hand was used in the copy trial than when the dominant (right) hand was used, regardless of the hand used in the recall test. Mattay et al. (1998) also reported that fine motor movements of the non-dominant hand are less familiar, more complex and require more conscious effort, resulting in recruitment of additional motor cortex areas for behavior. These studies suggest that non-dominant hand use, especially for right-handed people, could lead to cognitive decrements that resemble those observed in TBI and other neurological presentations.

4.4.1. How Fitts' task is related to motor rehabilitation

The Gilbreth's *therbligs* (Gilbreth's (1919)) were used to analyze the fundamental (basic) motions involved in the Fitts' training task for the study, as well as those involved in a common "*reaching and pointing"* task. In his theory, Gilbreth argued that all repetitive manual work involves 17 basic motions (aka *therbligs*), including reach, move, grasp, release, etc. Figure 7 identifies the complete set of therbligs symbols and provides descriptions. Descriptions are critical and useful for coding manual activities in terms of therbligs. If the number and type of basic motions are equivalent between the Fitts' task and the common "reaching and pointing" task, the Fitts' task could be considered as a potential candidate for real-world skill rehabilitation. In Table 4, a therblig analysis is presented, confirming such a similarity between the two tasks. The Fitts' task can be regarded as a small scale "*reaching and pointing"* task with the hand holding the Falcon controller throughout.

TABLE 10.1 Gilbreth's Seventeen Therbligs

Therblig	Letter Symbol	Description
Transport empty	TE	Reaching for an object with empty hand; for example, reach for a part prior to grasping and moving the part. Today, we commonly refer to the transport empty motion element as a "reach."
Grasp	G	Grasping an object by contacting and closing the fingers of the active hand about the object until control has been achieved.
Transport loaded	TL	Moving an object using a hand motion; for example, moving a part from one location to another at a workstation. Today, we commonly refer to a transport loaded motion element as a "move."
Hold	H	Holding an object; for example, holding an object with one hand while the other hand performs some operation on it.
Release load	RL	Releasing control of an object, typically by opening the fingers that held it and breaking contact with the object.
Preposition	PP	Positioning and/or orienting an object for the next operation and relative to an approximate location; for example, lining up a pin next to a hole for insertion into the hole. Preposition usually follows transport loaded.
Position	P	Positioning and/or orienting an object in the defined location that is intended for it. Position is generally performed during transport loaded; for example, moving a pin toward a hole and simultaneously lining it up in preparation for insertion into the hole.
Use	U	Manipulating and/or applying a tool in the intended way during the course of working, usually on an object; for example, using a screwdriver to turn a threaded fastener or using a pen to sign one's name.
Assemble	A	Joining two parts together to form an assembled entity; for example, using a threaded fastener to assemble two mating parts by hand.
Disassemble	DA	Separating multiple components that were previously joined in some way; for example, unfastening two parts held together by a threaded fastener.
Search	Sh	Attempting to find an object using the eyes or hand, concluding when the object is found.
Select	St	Choosing among several objects in a group, usually involving hand-eye coordination, and concluding when the hand has located the selected object.
Plan	Pn	Deciding on a course of action, usually consisting of short pause or hesitation in the motions of the hands and/or body.
Inspect	I	Determining the quality or characteristics of an object using the eyes and/or other senses.
Unavoidable delay	UD	Waiting due to factors beyond the control of the worker and included in the work cycle; for example, waiting for a machine to complete its feed motion.
Avoidable delay	AD	Waiting that is within the worker's control, causing idleness that is not included in the regular work cycle; for example, the worker opening a pack of chewing gum.
Rest	R	Resting to overcome fatigue, consisting of a pause in the motions of the hands and/or body during the work cycle or between cycles.

Figure 7. Set of therbligs and their descriptions from Gilbreth's (1919)

Table 4. Therblig-based comparison of the Fitts' task and reaching/pointing task

Proposed Fitts' task	Therbligs	Reaching and pointing task	Therbligs
Hold the Falcon controller	H		
Look for the target	S	Look for the target	S
Move the cursor to the target	M	Reach to the target	RE
Confirm the target-cursor position	I	Confirm the hand-target location	I
Click the Falcon button		Point the target	

4.5.Experimental design and variables

A randomized complete block within-subject experimental design was used in this study. Subject and trial served as blocking effects to account for individual differences in motor skill learning and potential trial effects.

4.5.1. Independent variables

Feedback type and feedback modality were the two independent variables manipulated in the experiment, each of which had three levels. Feedback type was KP, KR or a combination of the two. In the KP condition, feedback based on cursor control deviations from a predefined optimum motion trajectory was provided. Subjects received KP feedback cues only if the current cursor position was more than 20 pixels in distance away from the optimal trajectory (see Figure 8). In the KR condition, however, feedback cues were provided on whether the subject correctly hit a target or missed. Feedback modality was either visual, auditory or haptic.

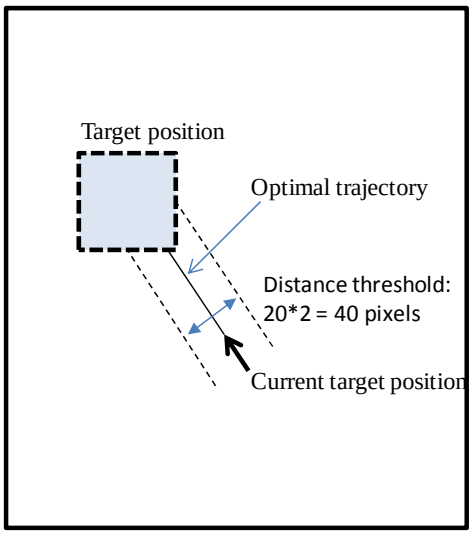

Figure 8. Trajectory threshold in the KP conditions

In the visual KP condition, the color of the CURSOR changed to FLASHING RED if the position was outside the predefined boundary. KP feedback was presented at the cursor since the cursor position corresponded to the state of the hand position mapped to the screen. In the visual KR condition, the color of the TARGET changed to GREEN if a subject hit it. Otherwise, the target color switched to RED for a miss. At the end of a trial, subjects were presented with a visual message on the screen regarding their overall target hit rate. KR feedback was presented at the target since the outcome of the "*clicking*" process was target related. The KR feedback remained on the screen for 200 ms until the next individual Fitts' trial started. During the dwell time, the subject was expected to process the feedback information and the Fitts' task was paused. In the visual KR + KP (combo) condition, combined feedback cues were delivered to subjects.

In the auditory KP condition, an artificially created tone was presented to a subject once his or her cursor deviated outside the predefined boundary. The tone followed a sine wave and had a frequency of 1000 Hz. In the auditory KR condition, the same tone was

presented to a subject when (s)he made a hit. If (s)he missed a target, the same tone with lower frequency (i.e., 500 Hz) was presented. The duration of the tone was approximately 200 ms. At the end of the trial, subjects heard an auditory tone conveying their overall hit rate. The combined feedback condition used both cues to assist learning and motivation.

In the haptic KP condition, a vibrating force was presented through the Falcon control to a subject if his or her cursor deviated outside the predefined trajectory boundary. The vibrating force was a looped individual recoil force lasting for 100 ms. The individual recoil force was presented along the z axis (in depth). This reduced the potential influence of the haptic feedback on cursor position control in the x-y plane. The individual recoil force was ramped up in 30 ms. In the haptic KR condition, another type of force effect was presented to a subject when (s)he made a hit. (S)he would feel nothing if (s)he missed a target. KR force-feedback was a much shorter vibrating force lasting approximately10 ms. At the end of the trial, the subject would feel a continuous vibration force, the length of which indicated their overall hit rate. The combined feedback condition integrated both force cues used in the task.

4.5.2. Dependent variables

The major dependent variables included subject intrinsic motivation and task learning level. The task learning level was inferred through the calculation of (1) learning percentage and (2) performance scores during a retention period. The major performance scores included target miss rate, average hit time (i.e., Fitts' time), cumulative deviation from the straight trajectory and jerkiness of the cursor movement.

Participant intrinsic motivation was measured using the IMI (intrinsic motivation) inventory. In this questionnaire, subjects rated 22 statements from "*not at all true*" (1) to

"*very true*" (7). Each statement measures one of four subscales related to human intrinsic motivation, including: (1) interest/enjoyment (7 statements), (2) perceived choice (5 statements), (3) perceived competence (5 statements), and (4) pressure/tension (5 statements). The presentation of the statements is fully randomized in the questionnaire. The interest/enjoyment subscale is considered to be the main self-report measure of intrinsic motivation. Perceived choice and perceived competence are theorized to be positive indicators of intrinsic motivation, whereas pressure and tension are negative indicators of intrinsic motivation. IMI data was collected once for each feedback test condition during the skill training period.

The target hit rate measures the accuracy level of the Fitts' task and it ranges from 0 to 1. Targets only appeared on the screen for 1.5 seconds, and there were a total of 40 targets in one training trial. Therefore, the maximum task completion time was approximately 1 minute. Fitts' time was the average time required for hitting a target. It ranged from 0 to 1500 ms.

Kinematic data were also recorded to determine how smoothly subjects were able to control their non-dominant hand during the task. Kinematic data were collected on the cursor position, velocity and acceleration as a proportional representation of the hand position in the x-y plane. The sampling rate was 10 Hz. Cumulative deviations from the straight trajectory between the cursor and target position were also determined. Jerkiness was defined as the total number of changes in movement direction relative to the straight trajectory in acquiring a single target (see Figure 9). All performance data was recorded automatically through the computer program after each trial.

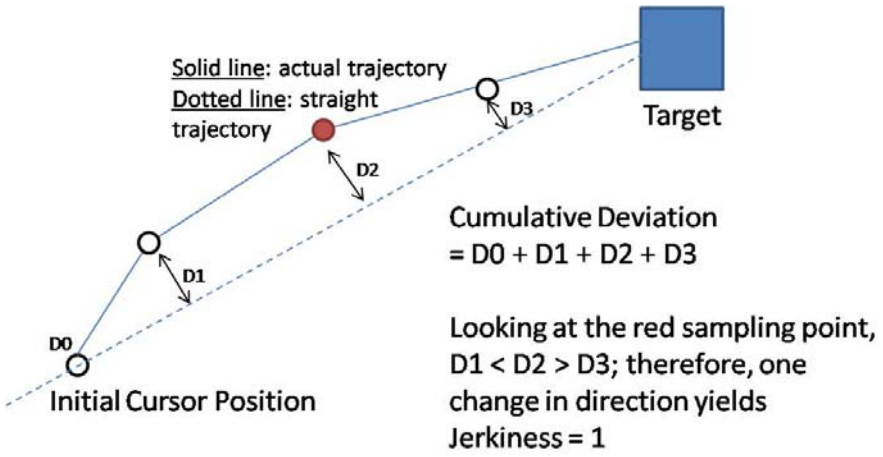

Figure 9. Calculation of cumulative deviation and jerkiness for one Fitts' target

4.5.3. List of specific hypotheses

Based on the literature review, the specific experimental hypotheses were as follows:

1) It was hypothesized that KR + KP would result in better skill learning (i.e., higher learning rates, higher performance scores during a retention period and higher performance scores on a transfer task) than KP, followed by KR.
2) Learning outcomes for motor control tasks with feedback were expected to be greatest for haptic cues, followed by auditory cues and visual cues.
3) It was hypothesized that KR + KP in motor training would be more motivating than KR, followed by KP.
4) It was expected that haptic cues would be more motivating than auditory cues in motor rehabilitation tasks, which in turn were expected to be more motivating than visual cues.
5) A non-linear relationship between human motivation level and motor skill learning was also expected.

4.6. Procedures and subject instruction

As previously mentioned, the experiment was set up and conducted in a quiet conference room (Figure 10). A researcher first briefly described the goal of the study to a subject, that is, to assess how feedback types and modalities might influence motor learning and human motivation. The subject was told that they would complete a set of simulated physical motor training sessions using the Novint Falcon device. They were told that only the non-dominant hand could be used in the experiment training. No detailed descriptions of feedback types were provided at this point in time. The researcher confirmed all subject screening criteria (e.g., no prior experience with the Falcon device) on a screening form before the experiment began.

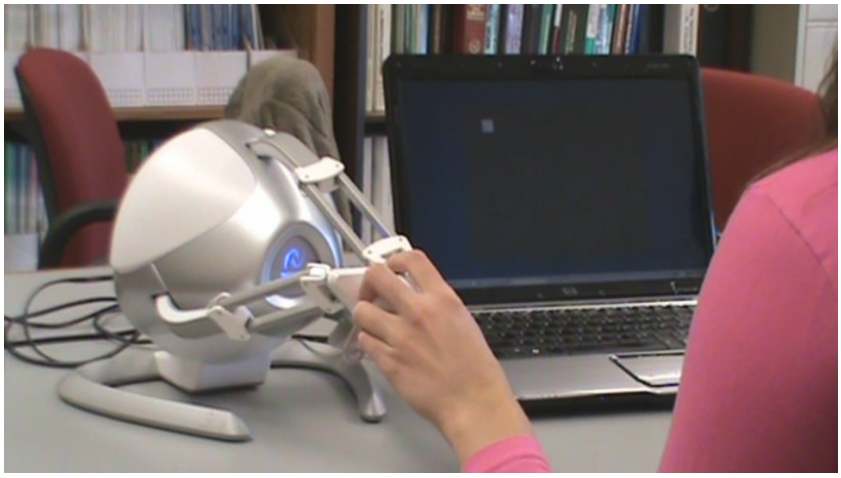

Figure 10. Test environment

Following the briefing, a device training session was provided in which participants were asked to “do a basic Windows File Moving Task” using the Novint Falcon controller with their dominant hand. Subjects were not allowed to use a keyboard for this task. Demonstrations of how the Falcon can function like a regular mouse (e.g., move up and

down, left click and right click) were provided. The timing of the training task was recorded. Subjects repeated the device training until a pre-defined completion time was reached. After this training process, every subject was expected to have attained the same level of familiarity with the device before the formal testing.

After the device training, the researcher described the Fitts' task to the subject. The subject was informed that the goal of the task was to detect and execute a click on the target as quickly and as accurately as possible. The researcher told the subject that the target would only remain on the screen for a short period of time. If the subject missed one target, they were instructed to go for the next one. Subjects were also informed that there would be a total of nine test conditions, each of which had to be repeated four times.

In the KP conditions, subjects were informed in advance of trials that they would receive a feedback cue if their cursor trajectory deviated too much from the optimal trajectory. In the KR condition, the subject was informed that the outcome of their clicks would be presented to them. Subjects were encouraged to hit as many targets as possible, while at the same time, maintaining good control of the device (i.e., not going outside the boundary of the task screen). Subjects repeated one feedback condition three times in a row before they moved on to another condition. Five minutes rest was provided between each condition, during which subjects were required to complete the IMI questionnaire form. After the rest period, subjects performed retention testing. This manipulation involved one additional trial under the test condition. A final survey was conducted after the subject finished all nine conditions. The total time for the experiment was approximately 2 hours. A general timeline for the experiment is presented in Figure 11.

Figure 11. Timeline (sequence of events) for the experiment

CHAPTER 5: PILOT DATA ANALYSIS AND RESULTS

5.1. Learning percentage

The learning percentage for each feedback condition was calculated for each subject using the formula shown in Section 2.4. Based on the current experimental setup, Y_n is the adjusted miss rate (i.e., 1 + miss rate) on the third trial (i.e., n = 3) of one condition. Y_1 is the adjusted miss rate on the first trial of that particular condition. The raw miss rate response was adjusted since a miss rate of zero could return an infinity error in the learning percentage calculation. Such an approach is similar to that used in calculation of Fitts' index of difficulty.

A theory-based approach was taken in calculation of the learning percentage by using only performance data from the initial and last training trials. Learning percentage can also be calculated by fitting a nonlinear curve to all the performance data. We did not use the latter approach for three reasons: (1) subjects only repeated three trials under each condition and the number of replications may not have been enough for reliable curve fitting; (2) the curve fitting approach can be very sensitive to outliers caused by fatigue or loss of motivation during a test; and (3) the theory-based approach has been used in a similar learning study conducted by Anderson et al. (2009).

Participants were expected to be involved in the second stage of learning (i.e., the associative stage, according to Anderson [1982, 2000]) during the training of the prototype Fitts' task. The rules for the task were easy and straightforward to understand. As previously mentioned, little learning occurs in the cognitive phase. According to Anderson's theory, task performance in the associative stage improves gradually and more consistently across trials.

Therefore, a monotonic learning trend was expected in the present task. If the performance level in one trial was lower than the proceeding trial, such data was regarded as an outlier and it was removed.

The pilot data revealed that haptic and auditory feedback led to higher rates of learning as compared with visual feedback (i.e., a lower percentage indicates a greater learning potential for future trials). The combo condition also had a higher rate of learning than the individual KP or KR conditions. A summary of the descriptive results for the learning percentage are presented in Tables 5 and 6.

Table 5. Descriptive statistics on learning percentage grouped by feedback modality

Modality	N	Mean	SD
H	9	96.14	2.96
A	9	96.92	3.29
V	9	97.91	2.22

Table 6. Descriptive statistics on learning percentage grouped by feedback type

Feedback	N	Mean	SD
Combo	9	95.58	3.43
KP	9	97.43	1.98
KR	9	97.95	2.66

5.2. Power analysis on the learning percentage response

In order to determine the appropriate sample size needed to detect statistically reliable effects, a series of power analyses was conducted using the "**Sample Size and Power**" command in SAS JMP. Each analysis required estimates of group means, an estimate of the within-group standard deviation, as well as specification of a desired power level. The means from Tables 5 and 6 were used as estimates for group means and the power level was set to be 0.8. An ANOVA model (i.e., Learning percentage = mu + Subject + Trial + Modality +

Feedback + Modality*Feedback + e) was applied to the data set and the model root mean square error was used as the estimate for the within-group deviation. Results revealed that approximately 78 observations were needed (i.e., 9 subjects) to detect differences in learning percentage due to feedback type. Furthermore, approximately 151 observations were projected (i.e., 17 subjects) to detect differences in learning percentage due to feedback modalities. A screenshot of the JMP output for the feedback type analysis is presented in Figure 12.

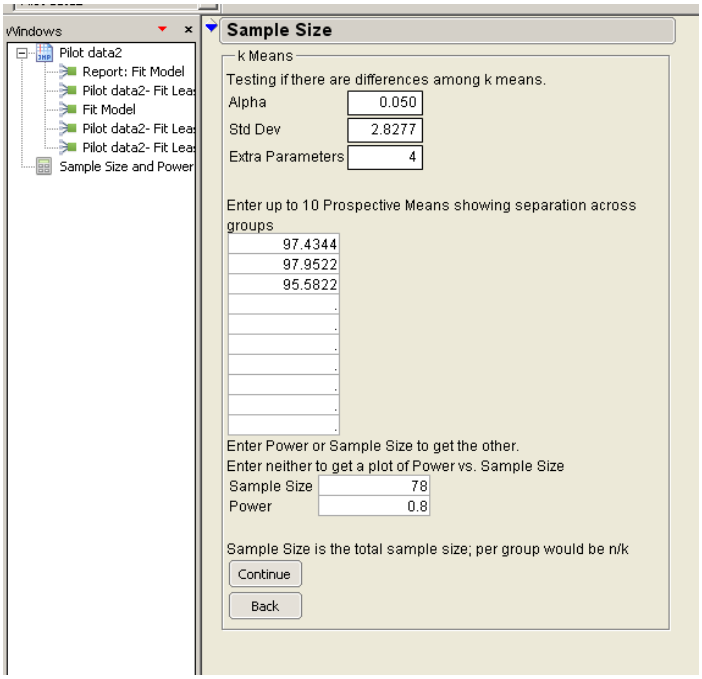

Figure 12. Power analysis from SAS JUMP

5.3. Absolute retention and power analysis

The standardized target miss rate during the retention trial (i.e., 4th trial) for each subject was used as the absolute retention score for each feedback condition (the miss rate for this trial was transformed to a z-score on an individual basis). This approach is regarded as a more valid measure of retention versus a relative retention score (Schmidt & Lee, 2005).

Descriptive statistics on the retention score, grouped by feedback type or modality, are presented in Tables 7 and 8, respectively. In general, the pilot data suggested that participants in the combo feedback condition had a lower miss rate during retention trial, followed by KR and then KP. Participants in the haptic feedback condition also had a lower target miss rate during retention, followed by visual feedback and auditory feedback. The power analysis using the same approach as described in Section 10.2 revealed a need for approximately 3 subjects and 8 subjects to achieve a power of 0.8 for detecting the main effect of feedback modality and feedback type, respectively.

Table 7. Standardized target miss rate during retention grouped by modality

Modality	N	Mean	SD
H	9	-0.337	0.286
V	9	0.081	0.325
A	9	0.795	0.250

Table 8. Standardized target miss rate during retention grouped by feedback type

Feedback	N	Mean	SD
Combo	9	-0.163	0.287
KR	9	0.289	0.259
KP	9	0.413	0.274

5.4. IMI scores and power analysis

The IMI scores were transformed to z-scores for each participant. Descriptive statistics are presented in Tables 9 and 10. According to the description of the survey, perceived interest is the major dimension that directly measures human intrinsic motivation. Looking at this dimension first, the haptic feedback condition led to higher levels of perceived interest than the visual and auditory feedback conditions. KR also resulted in higher perceived interest

than KP. These findings were consistent with the hypotheses. Power analysis revealed the need for approximately 20 subjects to achieve a power of 0.8 for detecting differences among feedback modalities. Approximately 18 subjects were projected to achieve the necessary power for detecting differences among feedback types.

Perceived pressure was theorized to be negatively correlated with intrinsic motivation. Perceived competence and choice were theorized to be positively correlated with intrinsic motivation. The pilot results showed that KR led to higher perceived competence, higher perceived choice, higher perceived interest and lower perceived pressure than KP. This was consistent with the theorized relationships among the dimensions of the IMI. Such consistency was also found between haptic and visual feedback modalities. The haptic modality led to higher perceived competence, higher perceived choice and lower perceived pressure than the visual modality. However, there was no clear trend for the auditory feedback modality. More data are needed to validate these preliminary findings.

Table 9. Descriptive statistics on IMI Z scores grouped by modality (mean and [SD])

	N	**Perceived Interest**	**Perceived Pressure**	**Perceived Choice**	**Perceived competence**
Auditory	9	0.15 [1.11]	0.15 [1.27]	-0.15 [0.64]	0.12 [1.11]
Haptic	9	0.19 [1.06]	0.04 [0.83]	0.12 [1.08]	0.05 [0.82]
Visual	9	-0.34 [0.66]	-0.20 [0.79]	0.03 [0.62]	-0.17 [1.02]

Table 10. Descriptive statistics on IMI Z scores grouped by type (mean and [SD])

		Perceived Interest	**Perceived Pressure**	**Perceived Choice**	**Perceived competence**
KP	9	-0.31 [0.97]	-0.09 [0.66]	-0.13 [0.41]	-0.40 [0.96]
KR	9	0.38 [0.77]	-0.56 [0.69]	0.17 [0.68]	0.64 [0.48]
Combo	9	-0.07 [1.09]	0.65 [1.11]	-0.04 [1.15]	-0.25 [1.06]

5.5.ANOVA modeling on other performance responses

A series of repeated-measures ANOVAs were conducted to investigate how feedback type and modality might have affected the Fitts' time. Results revealed significant main effects of feedback type ($F(2,16)=12.06$, $p=0.0006$) and modality ($F(2,16)=3.95$, $p=0.04$) on the Fitts' time (There was a total of 36 observations from four subjects completing nine trials each. The denominator degrees of freedom for the preceding tests were 16 (=35–3(for Subject)–8(for Trial)-2(for Type)-2(for Modality)-4(for Type*Modality)).). Post-hoc analysis revealed the Fitts' time to be significantly lower in the KP condition, followed by the combo condition, and then the KR condition (Figure 13). Results also revealed that visual feedback led to significantly lower Fitts' times as compared with auditory or haptic feedback (Figure 14). This makes sense since auditory feedback posed less interference with task performance as compared to visual or haptic feedback. In addition to this, a significant feedback type by modality interaction effect was found ($F(4,16)=3.42$, $p=0.035$). Figure 15 presents a plot of the average Fitts' time across four trials for each of the nine feedback conditions.

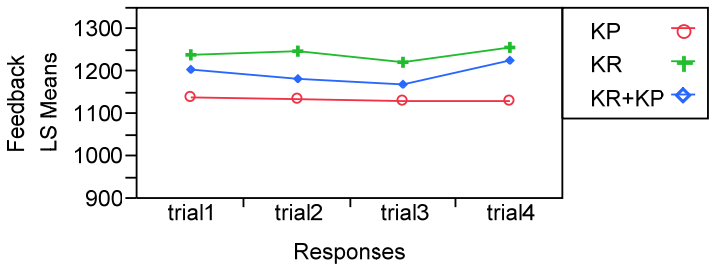

Figure 13. Post-hoc analysis for Fitts' time across feedback types

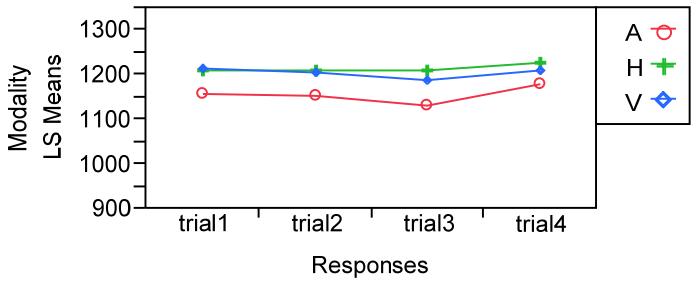

Figure 14. Post-hoc analysis for Fitts' time across feedback modalities

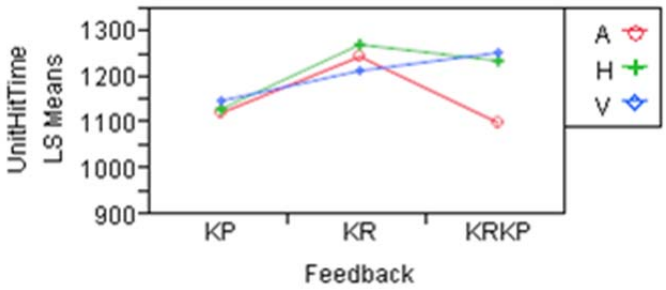

Figure 15. Fitts' time across trials grouped by feedback type and modality

The same ANOVA was conducted on the cumulative trajectory deviation response. There was a significant effect of feedback condition ($F(2,16)=8.16$, $p=0.0036$). The KP condition led to significantly lower cumulative deviations than the KR or combo conditions (post-hoc analysis using Tukey approach revealed significant difference between KR and KP, as well as between KP and the combo condition). However, no significant differences were found between the KR and combo conditions (see Figure 16), or across feedback modalities ($F(2,16)=0.21$, $p=0.8134$). These results suggest that the design of the KP feedback succeeded in modulating participants' movement trajectories during task performance.

Results also suggested that such modulating effects disappeared when both KR and KP were fed back to the participants. This finding might be due to participants tending to pay more attention to the KR feedback in the combined feedback condition, since the acknowledgement of hitting a target was regarded as more motivating than feedback on the state of the movement trajectory.

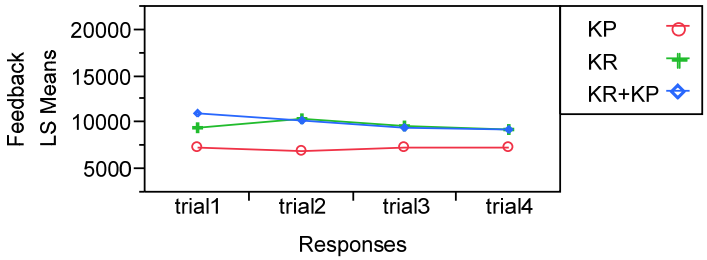

Figure 16. Plot of cumulative deviation response grouped by feedback types

Another repeated-measures ANOVA was conducted on the jerkiness response. However, no significant effects of feedback type or modality were found ($F(2,16)=0.51$, $p=0.607$ for feedback type; $F(2,16)=0.13$, $p=0.875$ for feedback modality). No significant interaction effect was found ($F(4,16)=1.52$, $p=0.244$). It is possible that this particular measure might not be sensitive or theoretically valid for assessing internal motor control. Parameter adjustments (e.g., an increase in the sampling rate) were made to this particular measurement for the full experiment.

CHAPTER 6: PILOT EXPERIMENT DISCUSSION

In this section, a detailed discussion on the preliminary pilot study results is provided. First, improvement in performance during training trials is examined on an individual basis. Following this, two aspects of learning measurement are discussed. Pros and cons of using a more balanced experimental design, instead of the common randomized complete block, were identified. A list of changes to the pilot experiment protocol is presented at the end of the Chapter as a basis for the full experiment.

6.1.Performance plot for individual subject

Subject adjusted trial miss rate (ATMR) data was plotted. Figure 17 presents a typical "spaghetti" plot for Subject #1. Arrows indicate the retention score for each feedback condition. The plot shows that this participant's initial miss rate was about 47% and he achieved a 5% miss rate by the 10^{th} trial. The learning of the task during this period (i.e., Condition 1 to Condition 3) was rapid. From Trial #12 to Trial #24 (i.e., Condition 4 to Condition 6), there were large variations in the ATMR score, likely due to fatigue and loss of motivation. Therefore, learning during this period was limited and not obvious. On this basis, a mandatory rest period (e.g., 15 minutes) was proposed for the full experiment to be included around the beginning of 5^{th} condition in order to address the potential fatigue issue. An adjustment of task difficulty level was also considered (i.e., an increase) to sustain task motivation. Figure 17 also shows that such fatigue and motivation issues might become less serious at later stages of training (i.e., Trial #15 to Trial #36). Participants might have felt motivated again since they were almost done with the test. Performance variations during this period became smaller and slow learning was observed.

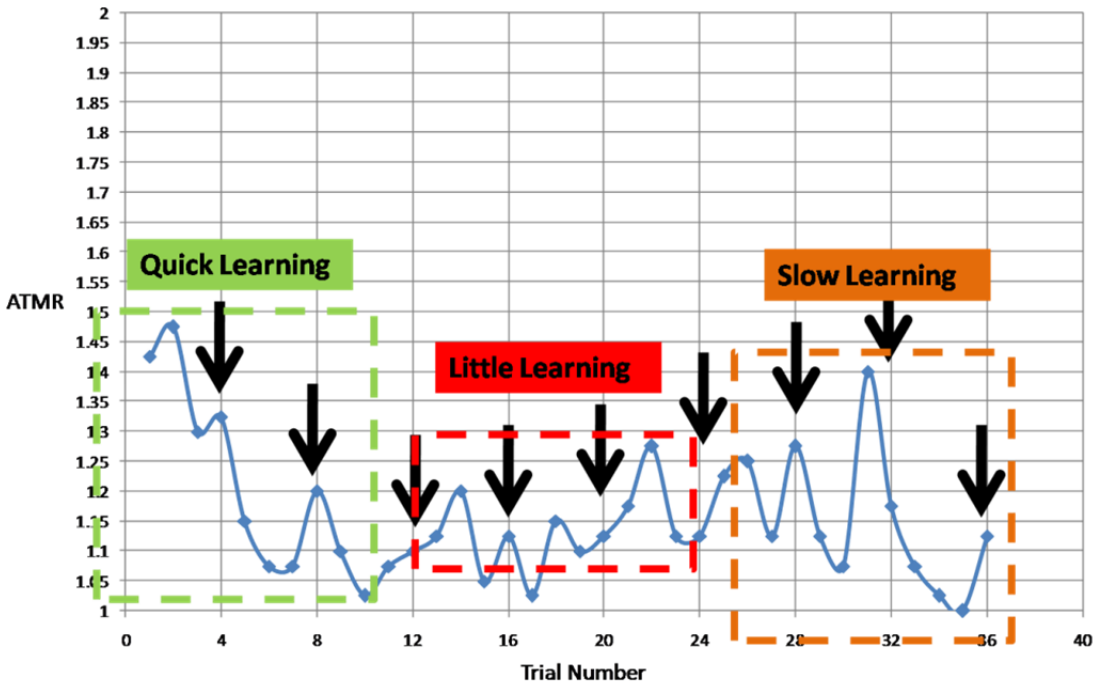

Figure 17. Plot of ATMR across trials and conditions for pilot Subject #1

6.2. Two aspects of learning measurements

Consistent with hypothesis 2, preliminary data analysis showed that haptic and auditory feedback led to higher learning rates than visual feedback. The combo feedback condition also resulted in a higher learning rate than KR or KP alone. The differences between KP and KR in terms of learning percentage, however, were small due to small sample size.

Motor learning was also assessed though the calculation of retention scores. The preliminary data analysis showed that the haptic combo condition led to the lowest retention score (i.e., least learning loss or highest amount of retention) among all the test conditions. This was expected and consistent with the inference based on the learning percentage response. However, the visual feedback resulted in higher retention than the auditory feedback. The KR condition also resulted in higher retention than the KP feedback. These findings were not expected and opposite to results from previous studies. This could be due

to failure in the randomization scheme used in the pilot test. In other words, the condition randomization scheme did not work simply due to the very small sample size used in the pilot test. It might be possible that, for the three pilot subjects in particular, the KR conditions were delivered during the later stage of training, whereas the KP conditions were delivered during the early stage of learning. A similar argument could be made for visual and auditory feedback as well. Therefore, it was determined that more data should be collected or a more balanced experimental design should be applied.

Previous patient studies found that KP was better than KR in terms of skill retention and learning. They adapted a between-subject design approach in which subjects trained with either KP or KR until asymptotic performance was achieved. Such an experiment protocol commonly requires several training sessions across several days. Delayed retention scores are usually measured on a separate day. This type of protocol can be very time consuming and expensive if the number of test conditions is large. To address this issue, the full experiment used a within-subject design. All feedback conditions were presented to each subject. In this study, trial effects were expected to be minimal across subjects.

Our initial hypothesis did not discriminate between the two measures of learning selected for the research. Learning percentage measures how quickly an individual can achieve asymptotic task performance, whereas retention score measures the skill level (or amount of learning) retained after a certain period of rest. The literature review revealed that retention score has been widely used in neuropsychological studies since researchers were more concerned with retention of function over time. In industrial learning scenarios, however, the measure of learning rate is more popular due to monetary reasons. Few motor

learning studies have attempted to discriminate the two measures. The present research represents the first attempt at applying the two learning measurements to a basic psychomotor task. A theory-based approach (Crown's formula) calculating learning percentage was applied to the full experiment dataset instead of a curve-fitting approach. This is a more complementary approach. The pilot data suggested that the effects of feedback type and modality on motor learning, although not significant, were quite different if measured through learning rate or retention score. More data was needed through the full experiment in order to clarify these findings.

6.3.Graeco-Latin square design and carryover effects

In the pilot study, a randomized complete block design was used in which each subject completed all nine feedback conditions. Pilot data revealed some carryover fatigue or carryover loss of motivation issues across participants during the test. These issues occurred roughly at the beginning of the 4th condition. In order to further address these issues, a Graeco-Latin square design was used as an alternative to the RCBD for the full experiment. With this design, each subject trained under a subset of all the test conditions (i.e., three conditions per subject) and the order for presenting the conditions was balanced across subjects for potential carryover effects. The statistical model for the design is as follows:

$$Y_{ij} = \mu + r_i + c_j + l_{dg(i,j)} + \tau_{dl(i,j)} + \varepsilon_{ij}$$

$$r_i = row\ blocking\ effect$$

$$C_i = column\ blocking\ effect$$

$$l_{dg(i,j)} = effects\ associated\ with\ Greek\ alphabet$$

$$\tau_{dl(i,j)} = effects\ associated\ with\ Latin\ alphabet$$

Four sources of variation existed for the full experiment, two of which are variations associated with subject individual differences and variations associated with condition trial. These two factors were, consequently, handled as blocking effects in the Graeco-Latin square design (i.e., the row factor and column factor). The other two sources of variation were from the feedback type and modality. These were represented by Greek and Latin alphabet characters, respectively (see Table 11). Following this scheme, one Graeco-Latin square is presented in Table 12. It shows that each subject only needs to be trained under three feedback conditions. The trials for each condition are balanced in the square. The design was replicated by recruiting more subjects (multiples of three).

Recruiting was planned for 18 subjects, and this corresponded to 6 Graeco-Latin squares in total. Each of the Graeco-Latin squares (without any permuting) was assigned a different order sequence (the three column labels). For example, in the first square, the column labels would be 1 2 3; in the second square, they would be 1 3 2; and so on, including 2 1 3, 2 3 1, 3 1 2, and 3 2 1. In this way, the design was completely balanced for the order of the treatments.

One of the drawbacks of using this design is that there may be a need for more subjects to achieve the desired statistical power (0.8) during the full experiment. The power analysis on the pilot test revealed a need for 18 to 20 subjects, when following a RCBD. This corresponds to 54 to 60 subjects with the Graeco-Latin design. However, this estimate may not be accurate due to the fact that the pilot data included outliers due to the fatigue issue. The removal of outliers during the learning percentage calculation could lead to an increase in the power estimation (less variability in the response). Therefore, 18 subjects were initially

recruited and tested for the full experiment, and the power analysis was recalculated using the data set to see if more subjects were needed for the experiment.

Table 11. Greek and Latin codes for feedback type and modality

Feedback Type	Feedback Type	Feedback Modality	Feedback Modality
A	KP	α	Visual
B	KR	β	Auditory
C	Combo	γ	Haptic

Table 12. A sample Graeco-Latin square design

	Condition Order 1	Condition Order 2	Condition Order 3
Subject #1	Aα	Bγ	Cβ
Subject #2	Bβ	Cα	Aγ
Subject #3	Cγ	Aβ	Bα

CHAPTER 7: FULL EXPERIMENT METHODOLOGY

For the most part, the pilot protocol was retained for the full experiment. Several minor changes were applied and are described in detail in the following sections.

7.1.Participants

Twenty four right-handed participants (9 female, 15 male; mean age = 25.45 yrs, SD = 8.6) were recruited from the university and surrounding areas for the full experiment. Based on a power calculation from the pilot test, 18 subjects were projected for the full experiment. Ultimately, 24 subjects were recruited for the full experiment due to changes in the feedback conditions. All participants were naïve to the experiment goal and had no experience with the Falcon device. As an addition to the pilot experiment protocol, each participant was required to fill-out a questionnaire about their handedness, the Edinburgh Handedness Inventory from Oldfield (1971), before formal testing. In this questionnaire, participants indicated which hand they preferred to use for each of the 12 tasks (e.g., writing, drawing, etc; only 10 of the 12 tasks are used in the scoring of this test). It was found that all participants were strongly right-handed (average Edinburgh Handedness score = 94.45, SD = 8.23). No ambidextrous subjects were included in the study, as indicated by Edinburgh Handedness score between -40 and + 40.

7.2.Experimental tasks

The level of task difficulty for the proposed Fitts' task was increased in the full experiment by reducing the target time on screen to 1300 ms (originally 1500 ms in the pilot test). This

was used to support sustained motivation for learning over time. Similar to the pilot study, the objective of the task was to hit the target as quickly and accurately as possible.

7.3.Equipment

In the full experiment, a head mounted display (VR8 HMD) was used during all trials (see Figure 18). The HMD was used to block any irrelevant visual cues from subjects, and to create a more immersive training environment for them. With this device, visual angles were also better controlled since the images were projected directly to participants' eyes. Auditory cues were delivered through built-in high performance Sennheiser earphones. Therefore, the speakers used in the pilot test were abandoned in the full study.

Figure 18. Experiment setting with HMD

7.4.Experimental design and variables

In the full experiment, Graeco-Latin square designs were used instead of the RCBD in order to address the potential carryover effects. Eight square designs with different order sequences were used (see Figure 19). In the Figure, Greek alphabet characters represent feedback type, whereas Latin alphabet characters represent feedback modality (see Table 11 for details).

	Condition Order 1	Condition Order 2	Condition Order 3
Subject #1	Aα	Bγ	Cβ
Subject #2	Bβ	Cα	Aγ
Subject #3	Cγ	Aβ	Bα

	Condition Order 1	Condition Order 2	Condition Order 3
Subject #4	Bγ	Aα	Cβ
Subject #5	Cα	Bβ	Aγ
Subject #6	Aβ	Cγ	Bα

	Condition Order 1	Condition Order 2	Condition Order 3
Subject #7	Aα	Cβ	Bγ
Subject #8	Bβ	Aγ	Cα
Subject #9	Cγ	Bα	Aβ

	Condition Order 1	Condition Order 2	Condition Order 3
Subject #10	Cβ	Aα	Bγ
Subject #11	Aγ	Bβ	Cα
Subject #12	Bα	Cγ	Aβ

	Condition Order 1	Condition Order 2	Condition Order 3
Subject #13	Bγ	Cβ	Aα
Subject #14	Cα	Aγ	Bβ
Subject #15	Aβ	Bα	Cγ

	Condition Order 1	Condition Order 2	Condition Order 3
Subject #16	Cβ	Bγ	Aα
Subject #17	Aγ	Cα	Bβ
Subject #18	Bα	Aβ	Cγ

	Condition Order 1	Condition Order 2	Condition Order 3
Subject #19	Aα	Bγ	Cβ
Subject #20	Bβ	Cα	Aγ
Subject #21	Cγ	Aβ	Bα

	Condition Order 1	Condition Order 2	Condition Order 3
Subject #22	Bγ	Aα	Cβ
Subject #23	Cα	Bβ	Aγ
Subject #24	Aβ	Cγ	Bα

Figure 19. Graeco-Latin square designs for the full experiment

In the full experiment, several adjustments were made to ensure stimuli equivalence across visual, auditory or haptic cues. Specifically, the goal was to configure the stimuli to be comparable across conditions in terms of On/Off setting, waveform and duration.

One problem encountered during the pilot test was that no haptic cues were provided to participants in the case of missing a target. Participants were, however, provided some sort of feedback with a target miss in the auditory or visual conditions. This might compromise stimulus equivalence across test conditions. To address this issue, all feedback on a target miss in the KR conditions was removed (see Table 13). That is, feedback was delivered (either in visual, auditory, or haptic forms) only when subjects hit a target.

In the pilot test, the waveforms of the unit stimuli were not comparable across modalities. For example, the auditory cues followed a sine wave (note: Auditory KP sounded like intermittent tones due to the lower sampling rate in the computer program); the visual cues were solid red with no directional gradient (note: Visual KP looked like flashing red due to the lower sampling rate in the computer program); the unit haptic cues were recoil forces with a ramp-up period of 30 ms (note: Haptic KP felt like intermittent or transitory vibration due to the lower sampling rate in the computer program). These differences in stimuli waveforms might affect the inferences on the effects of feedback modality on skill learning and retention. To address this, all the cues were reconfigured to be “linear” just like the visual cues (i.e., solid red) used in the pilot test (see Table 14). For example, the auditory cues were adjusted to follow a square wave form (generated through computer software named Audacity). Similarly, the ramp-up period for the unit haptic cues was removed. The force cues used in the full experiment were constant and linear in waveform.

Other stimulus parameters, including shape color, tone pitch, and force level were configured to be different between KP and KR. The reason for this was that participants needed some sort of stimulus discrimination in the combo condition.

Another issue was that the duration of a unit haptic cue was different from the auditory or visual cues in the pilot test. The unit recoil force lasted for 100 ms, whereas the visual (or auditory) cues lasted 200 ms. To address this, the duration of the unit force cue was extended to 200 ms in the full experiment.

Table 13. Experimental stimuli design

	Visual	Auditory	Haptic
KP	Red cursor with path deviation	High pitch tone (1000 Hz) with path deviation	Lower kicking force (0.5 N) with path deviation
KR	Nothing with miss Green target with hit Visual Message	Nothing with miss Low pitch tone (500 Hz) with hit Auditory Message	Nothing with miss Higher kicking force (1 N) with hit Vibration

Table 14. Unit stimuli comparison across feedback modalities

	Visual	Auditory	Haptic
Waveform	Solid color with no gradient	Linear square wave form	Constant force with no ramp-up
Duration	200 ms	200 ms	200 ms
ON/OFF	ON with hit in KR ON with path deviation in KP	ON with hit in KR ON with path deviation in KP	ON with hit in KR ON with path deviation in KP

7.5. Procedures

The main procedures followed the protocol of the pilot study with several minor changes. For example, a calibration period of the HMD was included to ensure that each participant felt comfortable with the device on his/her head. The laptop position relative to the desk, as well as the position of the Falcon device relative to the laptop was fixed. The range of the motion

was consistent across participants. Before the formal test, a demonstration of the Fitts' task with no feedback was presented. Subjects were instructed that the goal of the task was to hit target as quickly and accurately as possible. After that, participants completed only three feedback conditions in the full experiment (instead of nine in the pilot test). The number of repetitions for each feedback condition was increased (i.e., from 4 trials in the pilot test to 6 trials in the full experiment). The repetitions included five training trials and one retention trial. The retention rest period was increased from 5 minutes to 10 minutes to reduce subject fatigue effects. A preference survey was conducted during the retention period to collect subject general feedback on the test condition. An extrinsic bonus was used to sustain motivation. Specifically, subjects were paid $15/hour for the experiment and they had the opportunity to win an additional $15 if their task performance was in the top 3 among all participants. Most participants completed the experiment within 1 hour with a few exceptions who took about 1.25 hours. Subjects could not inflate task time (for more compensation) due to the fact that the task trial time was fixed. No intentional slow learning from lack of motivation was observed.

7.6. Expected outcomes and application

After the above minor changes to the pilot experiment protocol, it was expected that participants in the full experiment would be more motivated and engaged in the training task. Increased engagement was also expected to lead to a more reliable and consistent dataset for the statistical analysis.

In general, the present research was expected to reveal a significant impact of sensory feedback on human motor skill learning and motivation. Such findings would contribute to

the general understanding of human internal learning processes. From a practical perspective, the research results might serve as a basis for feedback design guidelines for industrial training or rehabilitation regimens. From a research standpoint, the proposed experimental procedure could also be extended and applied to general studies involving skill learning assessment.

CHAPTER 8: FULL EXPERIMENT RESULTS

8.1.Descriptive statistics

The descriptive statistics for all the responses (grouped by feedback type or feedback modality) are shown in Table 15. The intrinsic motivation corresponds to the “perceived interests” subscale within the IMI inventory and it ranges from 7 (least motivated) to 49 (highly motivated). The retention scores represent subject performance in the retention trials. These included (1) target miss rate (ranging from 0 - 1), (2) average time for a hit (i.e., Fitts’ time; ranging from 0 – 1500 ms), (3) path deviation and (4) jerkiness. Path deviation was measured in terms of pixel distances of a subject’s cursor from the optimal trajectory throughout a trial. Jerkiness was measured as the number of times the direction of motion of a subject’s cursor, towards or away from the optimal trajectory, changed (i.e., a count). Learning percentages were calculated using formula-based approach and they ranged from 0 to 100. Lower learning percentages indicate a higher potential for future learning. Similar to the retention scores, the learning percentages were separated to reflect either task performance learning (i.e., miss rate and Fitts’ time), or motor control learning (i.e., path deviation and jerkiness).

Table 15. Descriptive statistics grouped by feedback type or modality

Mean (standard error)		Feedback			Modality		
		KP	KR	Combo	Auditory	Haptic	Visual
Intrinsic motivation (range from 7 – 49)		31.92 (1.51)	35.92 (1.26)	35.13 (1.63)	33.79 (1.66)	35.50 (1.40)	33.67 (1.45)
Retention score	Miss rate (%)	36.4 (3.3)	23.5 (3.2)	25.7 (2.7)	26.9 (3.4)	29.3 (3.4)	29.5 (3.0)
	Fitts' time (ms)	987 (22)	1148 (19)	1062 (24)	1020 (22)	1070 (27)	1105 (24)
	Deviation (pixels)	8667 (690)	9285 (683)	8931 (722)	8371 (771)	8836 (647)	9675 (650)
	Jerkiness (counts)	120 (2.44)	119 (1.99)	112 (3.64)	119 (2.26)	112 (3.60)	121 (2.10)
Learning percentage	Miss rate	85.22 (2.64)	80.42 (2.55)	78.26 (3.44)	80.06 (2.77)	83.44 (2.73)	80.41 (3.31)
	Fitts' time	96.67 (0.52)	97.39 (0.46)	97.32 (0.48)	96.54 (0.57)	97.28 (0.44)	97.56 (0.44)
	Deviation	89.34 (1.79)	90.05 (1.91)	90.46 (1.73)	89.47 (1.58)	89.44 (2.10)	90.93 (1.69)
	Jerkiness	96.38 (0.84)	96.01 (0.68)	96.32 (0.72)	95.59 (0.76)	95.66 (0.74)	97.46 (0.67)

Table 16. Mixed Model ANOVA results with power calculations for main effects

		Feedback	**Modality**	**Feedback *Modality**	**Trial**	**Feedback* Trial**	**Modality* Trial**
Intrinsic motivation (Perceived Interest)		F(2,32) = 16.02 p < 0.0001 *** power = 0.93	F(2,32) = 4.61 p = 0.0174 ** power = 0.35	F(4,32) = 2.64 p = 0.0517 *	F(2,32) = 0.46 p = 0.633	F(4,32) = 0.12 p = 0.976	F (4,32) = 0.89 p = 0.480
Retention score	Miss rate	F(2,32) = 13.15 p < 0.0001 *** power = 1	F(2,32) = 0.46 p = 0.637 power = 1	F(4,32) = 3.54 p = 0.017 **	F(2,32) = 11.55 p = 0.0002 ***	F(4,32) = 1.01 p = 0.416	F (4,32) = 1.00 p = 0.421
	Fitts' time	F(2,32) = 30.82 p < 0.0001 *** power = 0.99	F(2,32) = 8.06 p = 0.0015 *** power = 0.96	F(4,32) = 5.21 p = 0.0024 ***	F(2,32) = 0.84 p = 0.441	F(4,32) = 0.49 p = 0.739	F (4,32) = 1.48 p = 0.230
	Deviation	F(2,32) = 0.79 p < 0.461 power = 0.07	F(2,32) = 5.29 p = 0.010 ** power = 0.147	F(4,32) = 5.91 p = 0.001 ***	F(2,32) = 8.38 p = 0.0012 ***	F(4,32) = 0.24 p = 0.91	F (4,32) = 1.04 p = 0.404
	Jerk	F(2,32) = 2.44 p = 0.103 power = 0.61	F(2,32) = 2.95 p = 0.0665 * power = 0.69	F(4,32) = 3.09 p = 0.029 **	F(2,32) = 1.25 p = 0.30	F(4,32) = 1.23 p = 0.32	F (4,32) = 0.13 p = 0.96
Learning percentage	Miss rate	F(2,32) = 2.50 p = 0.09* power = 0.45	F(2,32) = 0.88 p = 0.425 power = 0.15	F(4,32) = 0.11 p = 0.978	F(2,32) = 4.01 p = 0.028 **	F(4,32) = 0.42 p = 0.79	F (4,32) = 2.03 p = 0.113
	Fitts' time	F(2,32) = 0.73 p = 0.490 power = 0.126	F(2,32) = 0.28 p = 0.757 power = 0.2	F(4,32) = 0.72 p = 0.582	F(2,32) = 2.60 p = 0.089 *	F(4,32) = 0.95 p = 0.447	F (4,32) = 0.58 p = 0.676
	Deviation	F(2,32) = 0.18 p = 0.837 power = 0.062	F(2,32) = 0.66 p = 0.523 power = 0.077	F(4,32) = 0.98 p = 0.430	F(2,32) = 7.25 p = 0.0025 ***	F(4,32) = 0.41 p = 0.803	F (4,32) = 0.40 p = 0.804
	Jerk	F(2,32) = 0.35 p = 0.711 power = 0.056	F(2,32) = 2.82 p = 0.074 * power = 0.31	F(4,32) = 1.24 p = 0.315	F(2,32) = 1.55 p = 0.227	F(4,32) = 0.54 p = 0.706	F (4,32) = 0.81 p = 0.5310

Note: * p-value less than 0.10 ** p-value less than 0.05 *** p-value less than 0.01
Power values represent sensitivity for detecting a significant difference among conditions based on the observed data.
An effect size was not specified in advance.

8.2.Statistical analysis approach

A mixed ANOVA model was constructed on each of the response measures. Subject number (i.e., 1 - 24) was treated as a random effect in the model. Trial number, feedback type and feedback modality were treated as fixed factors, each of which had three levels. The goal of the present research was to investigate feedback effects on an aggregate basis. Therefore, fixed effects were limited up to two-way interactions (i.e., model DV = feedback|modality|trial@2, subject as random factor). The three-way interaction of the fixed factors was not assessed, but was pooled into the model error term.

8.3.Analysis on intrinsic motivation

Intrinsic motivation ratings were transformed to Z scores before the statistical analysis. Results revealed a significant main effect of feedback type ($F(2,32)=16.02$, $p<0.001$) on subject intrinsic motivation. Consistent with our hypothesis, post-hoc analysis revealed subjects in the KR or combo conditions reported significantly higher levels of intrinsic motivation in the task than those in the KP group ($p<0.05$). No significant differences in motivation level were found between the KR and combo groups (see Figure 20).

A significant main effect of feedback modality was also found for intrinsic motivation ($F(2,32)=4.61$, $p=0.0174$). Participants reported significantly higher levels of intrinsic motivation with haptic cues than with visual or auditory cues ($p<0.05$, see Figure 21). Furthermore, we have also found a marginally significant interaction effect between feedback type and modality ($F(4,32)=2.64$, $p=0.052$). For KP, haptic cues were significantly more motivating than visual or auditory cues. For KR, all three types of sensory modalities were

equally motivating. For the combo feedback condition, haptic or auditory cues were marginally significantly more motivating than visual cues.

A series of correlation analyses were conducted among the sub-scales within the motivation inventory (Figure 22). Consistent with results from previous studies, the major subscale measuring intrinsic motivation (i.e., perceived interest) was highly correlated with perceived competence (r=0.387, p=0.001), which in turn was negatively correlated with perceived pressure (r = -0.543, p=0.001) and positively related to perceived choice (r=0.359, p=0.002). The perceived pressure subscale was also negatively correlated with perceived choice (r = -0.335, p=0.004).

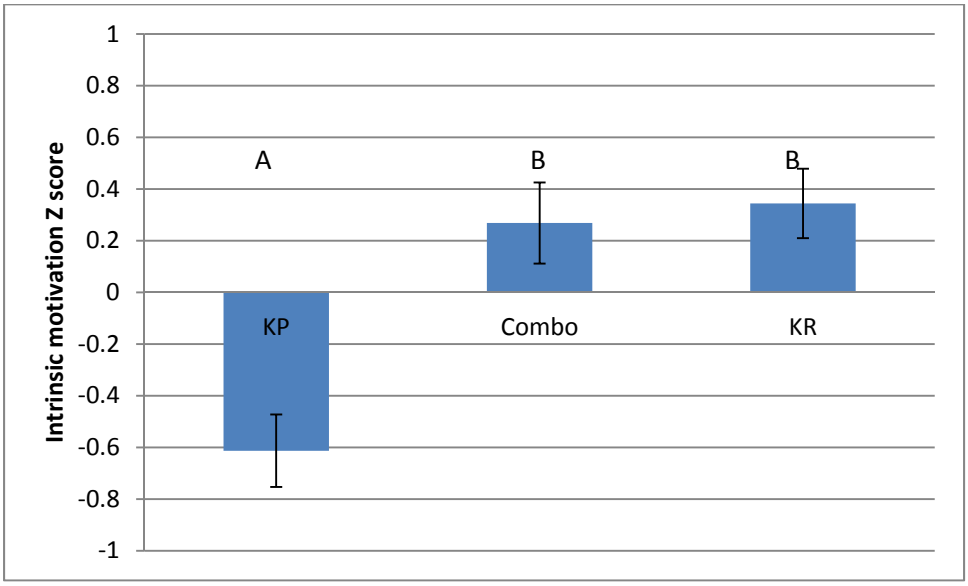

Figure 20. Plot of intrinsic motivation z scores across feedback groups

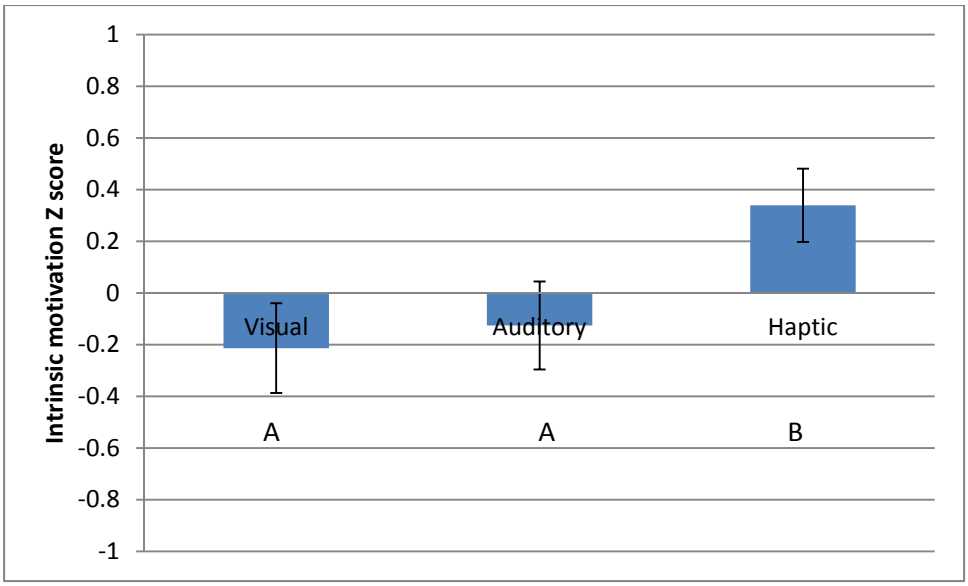

Figure 21. Plot of intrinsic motivation z scores across feedback modalities

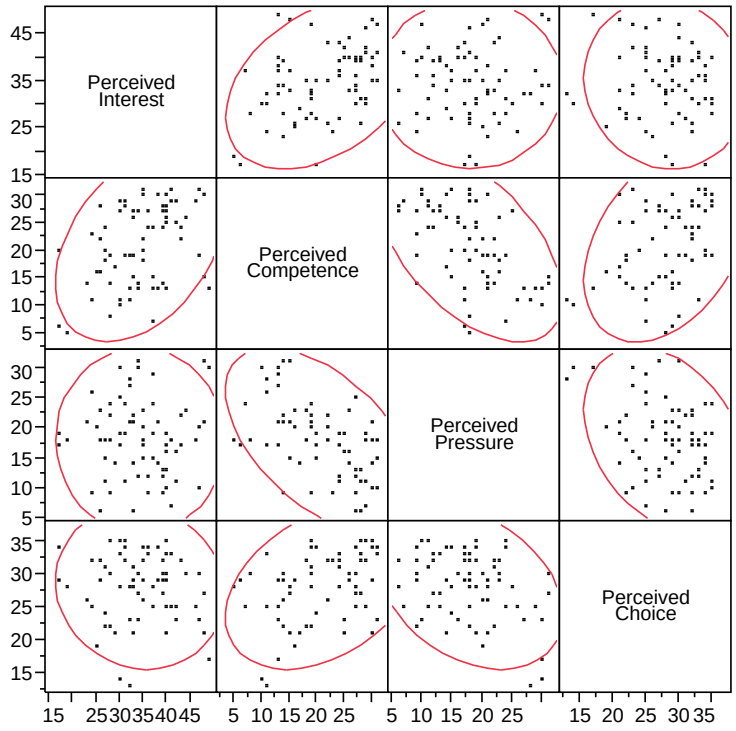

Figure 22. Correlation analysis among the subscales of the IMI inventory

8.4. Analysis on retention scores

The same mixed model ANOVA was applied to the retention scores, including miss rate, Fitts's time, cumulative deviation and jerkiness.

8.4.1. Miss rate

Results revealed that there was a significant main effect of feedback type on miss rate during the retention trial ($F(2,32)=13.15$, $p<0.0001$). Post-hoc analyses showed that participants in the KR or combo groups missed significantly fewer targets during the retention trial than those in the KP group (see Figure 23). However, no significant main effect of sensory modality was found for this response ($F(2,32)=0.46$, $p=0.6373$). Results did reveal a significant interaction effect between feedback type and modality on target miss rate during the retention trial ($F(4,32)=3.54$, $p=0.016$, see Figure 24 and annotations). It appeared that the additional learning benefits associated with the KR and combo groups (over the KP group) were more prominent under auditory cueing than for visual or haptic cueing.

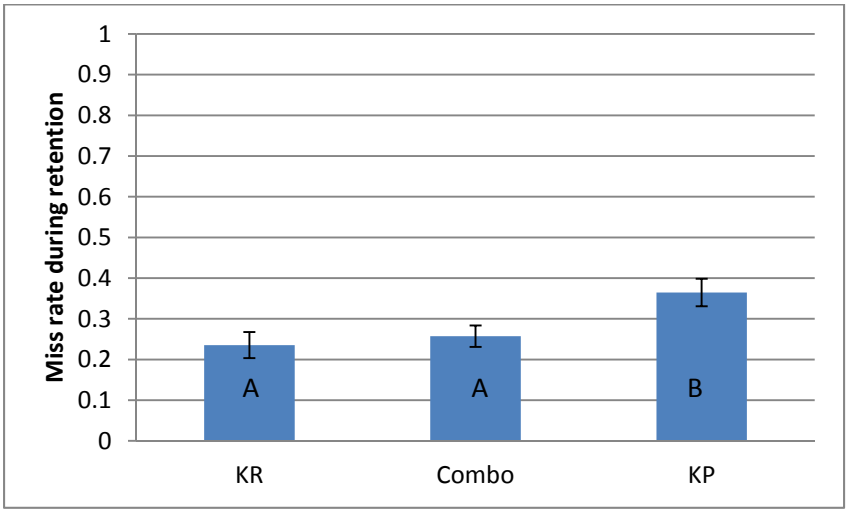

Figure 23. Plot of miss rate in the retention trial grouped by feedback types

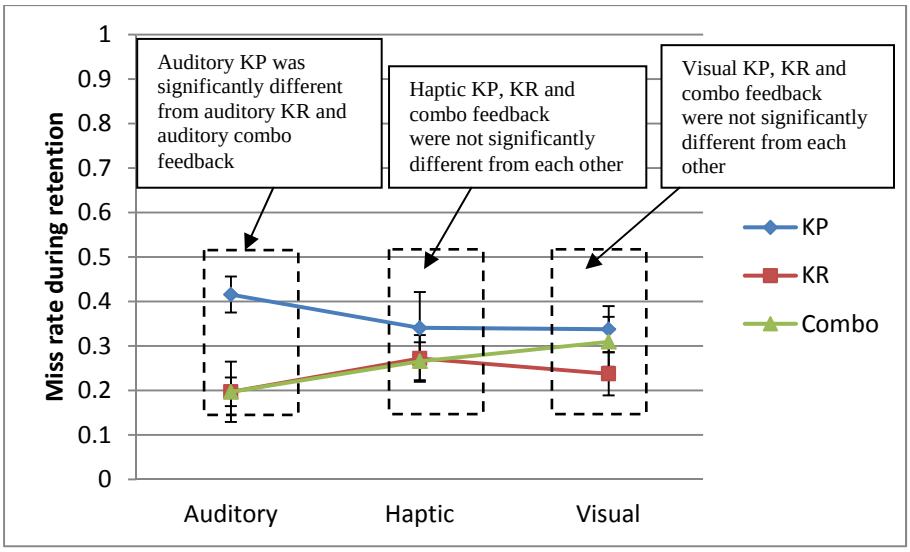

Figure 24. Plot of miss rate in the retention trial across feedback types and modalities

8.4.2. Fitts' time

Consistent with our hypotheses, there were significant main effects of feedback type ($F(2,32)=30.82$, $p<0.0001$) and feedback modality ($F(2,32)=8.06$, $p=0.0015$) on Fitts' time during the retention trials. Participants in the KP group spent significantly less time on hitting one target during the retention trial than those in the combo group, followed by the KR group (see Figure 25). Results also revealed that participants in the auditory group performed significantly faster in the retention trials as compared with those in the haptic or visual groups (see Figure 26). Furthermore, a significant interaction effect between feedback type and modality was also observed ($F(4,32)=5.21$, $p=0.0024$). The learning benefits of auditory cues appeared most prominent for the combo feedback groups rather than the individual KR or KP groups (see Figure 27 and annotations). It might be possible that auditory cues were helpful in reducing information overload in the combo groups, which in turn supported learning and retention. Similarly, the beneficial learning effect of KP (over KR and the

combo condition) was more prominent for the haptic and visual groups than the auditory group (Figure 27).

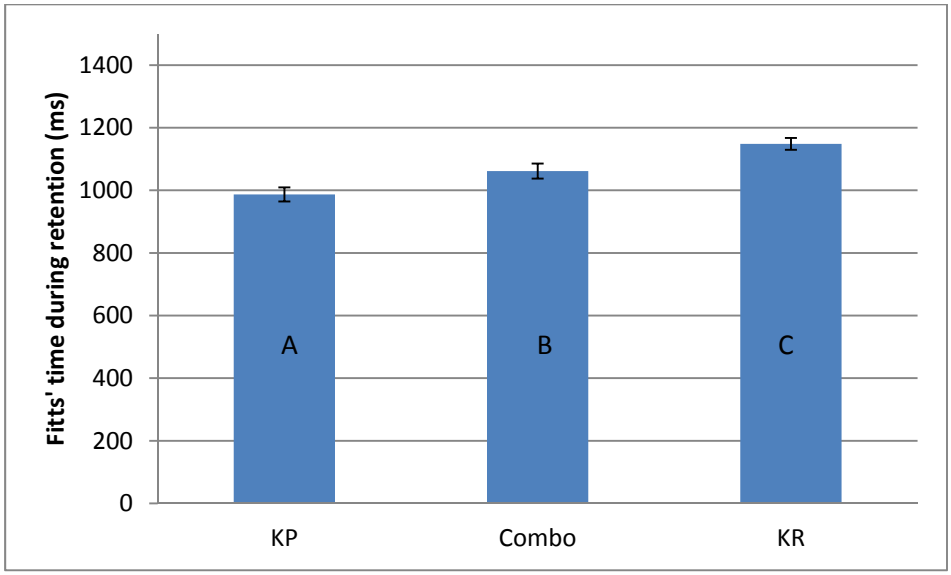

Figure 25. Plot of Fitts' times in retention trials grouped by feedback types

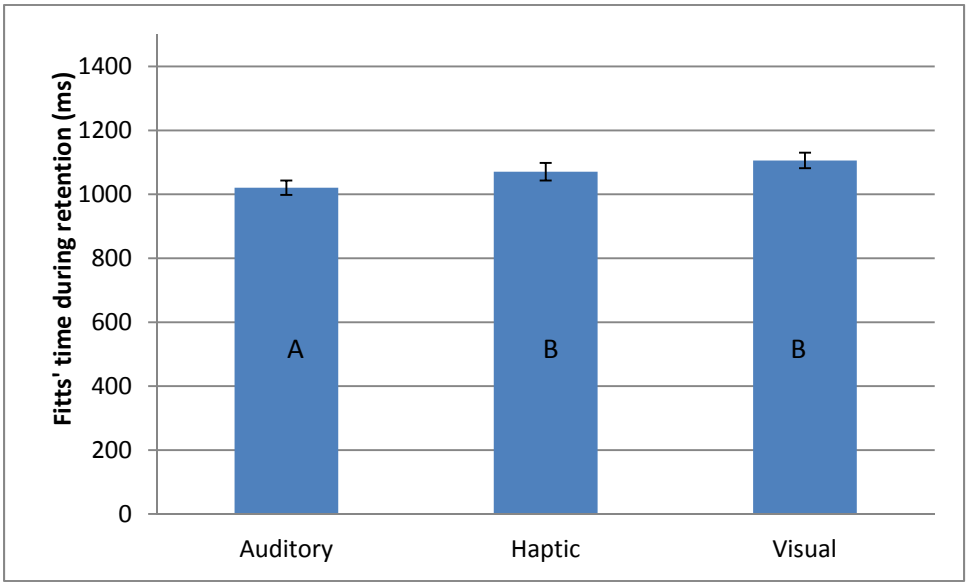

Figure 26. Plot of Fitts' times in retention trials grouped by feedback modalities

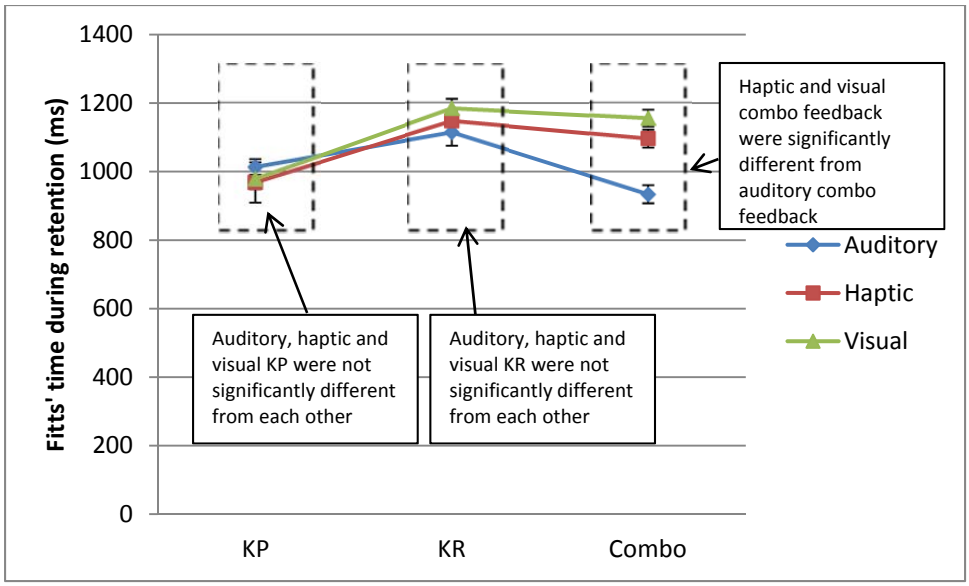

Figure 27. Plot of times in retention trials across feedback types and modalities

8.4.3. Cumulative deviation

After diagnostics on the deviation data collected during the retention trials, it appeared that responses did not follow a normal distribution and the variances associated with the test groups were not equivalent. To address this issue, cumulative deviation data (all positive) in the retention trials were logarithmically transformed and the response normality and non-constant variance issues were resolved. Results revealed a significant main effect of feedback modality ($F(2,32)=5.29$, $p=0.01$). Post-hoc analysis showed that participants in the auditory or haptic groups completed retention trials with significantly less path deviations than those in the visual group (see Figure 28). However, no main effect of feedback type ($F(2,32)=0.79$, $p=0.461$) was found. There was a significant interaction effect observed between feedback modality and type ($F(2,32)=5.91$, $p=0.001$). It appeared that the modality effect was most prominent under the combo feedback condition (see Figure 29 and annotations).

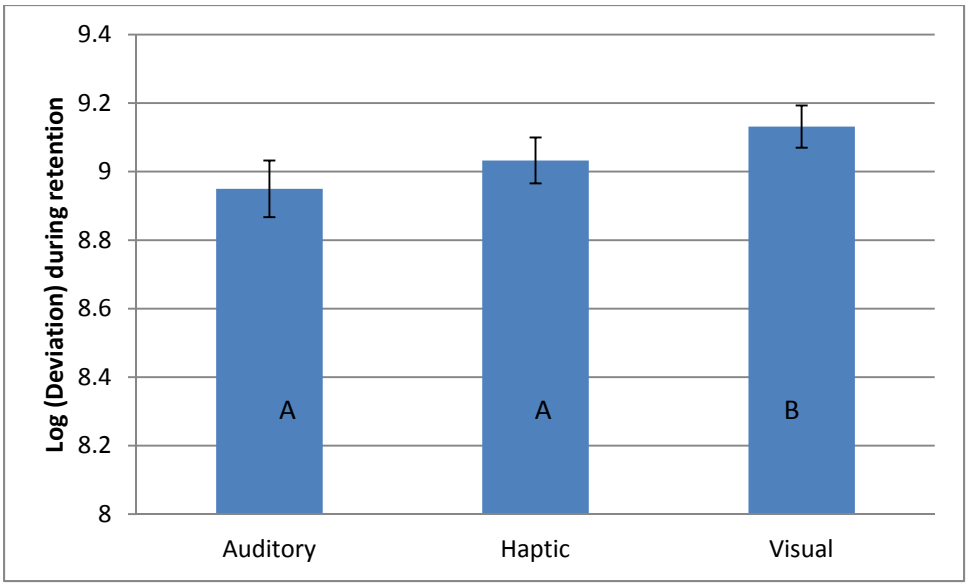

Figure 28. Plot of deviation in the retention trial grouped by feedback modalities

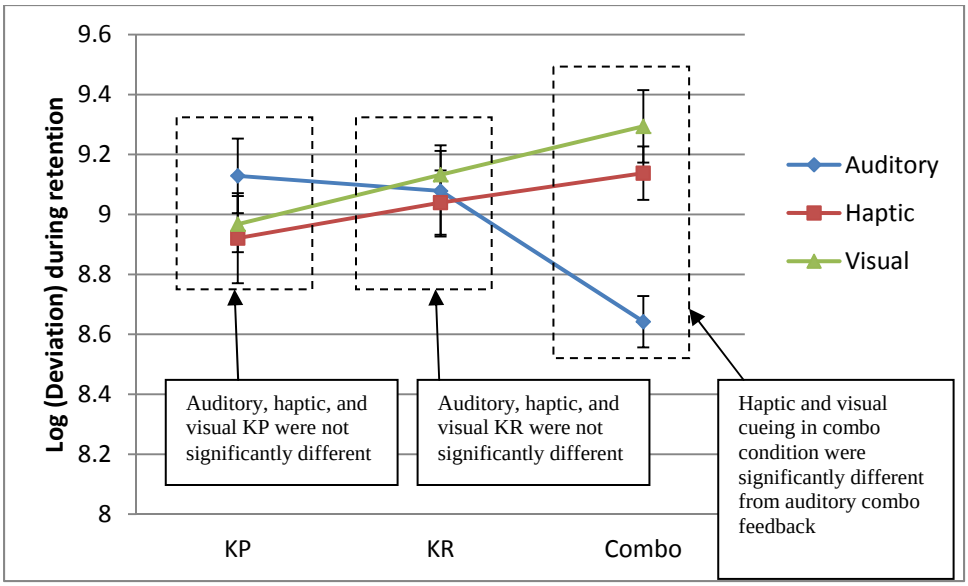

Figure 29. Plot of deviation in the retention trial across feedback types and modalities

8.4.4. Jerkiness

With respect to the jerkiness data in the retention trial, there was a marginally significant main effect of feedback modality ($F(2,32)=2.95$, $p=0.0665$). Consistent with our hypothesis, participants in the haptic group demonstrated less jerkiness in the retention trial than those trained with auditory or visual cues (Figure 30). Furthermore, there was also a significant interaction between feedback type and modality ($F(4,32)=3.09$, $p=0.029$). It appeared that the additional learning effects of haptic cues (over visual or auditory cues) were more prominent under the combo feedback condition than the individual feedback conditions (see Figure 31). However, no significant main effect of feedback type ($F(2,32)=2.44$, $p=0.103$) was found on jerkiness scores in the retention trial. In general, participants in the combo feedback group completed the retention Fitts' trial with less jerkiness than those in the KR or KP groups (see Figure 32).

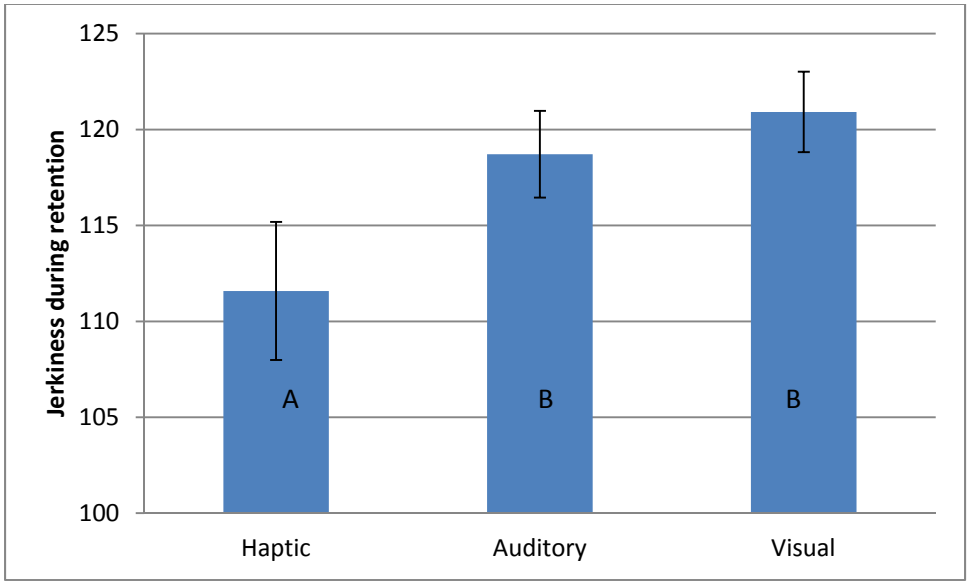

Figure 30. Plot of jerkiness for the retention trials grouped by feedback modalities

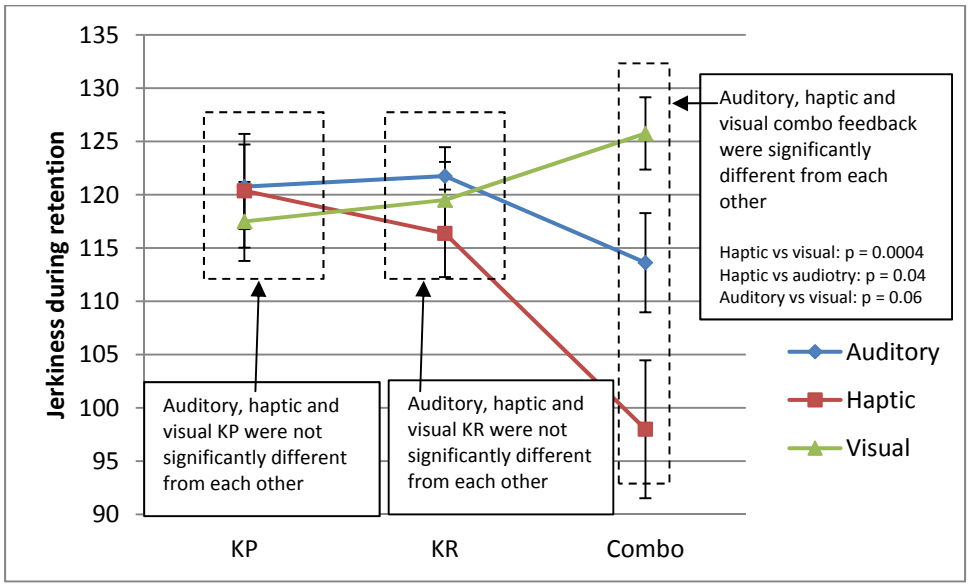

Figure 31. Plot of jerkiness for the retention trials across feedback types and modalities

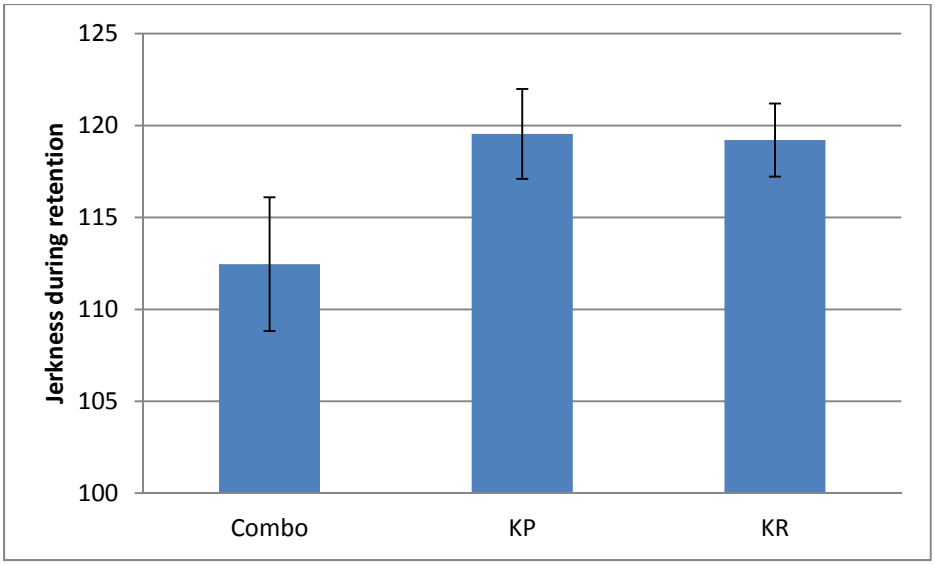

Figure 32. Plot of jerkiness for the retention trials grouped by feedback types

8.5. Learning percentage score analysis

Similar mixed ANOVA models were constructed and applied to the learning percentage scores, calculated based on raw miss rate, Fitts' time, cumulative deviation or jerkiness data.

8.5.1. Learning percentage calculated with miss rate data

Results revealed a marginally significant main effect of feedback type on miss rate learning percentage ($F(2,32)=2.50$, $p=0.09$). Post-hoc analysis showed that participants in the KR and combo groups had a marginally significantly lower miss rate learning percentage than those in the KP group (see Figure 33). However, no main effect of feedback modality was found ($F(2,32) =0.88$, $p=0.42$).

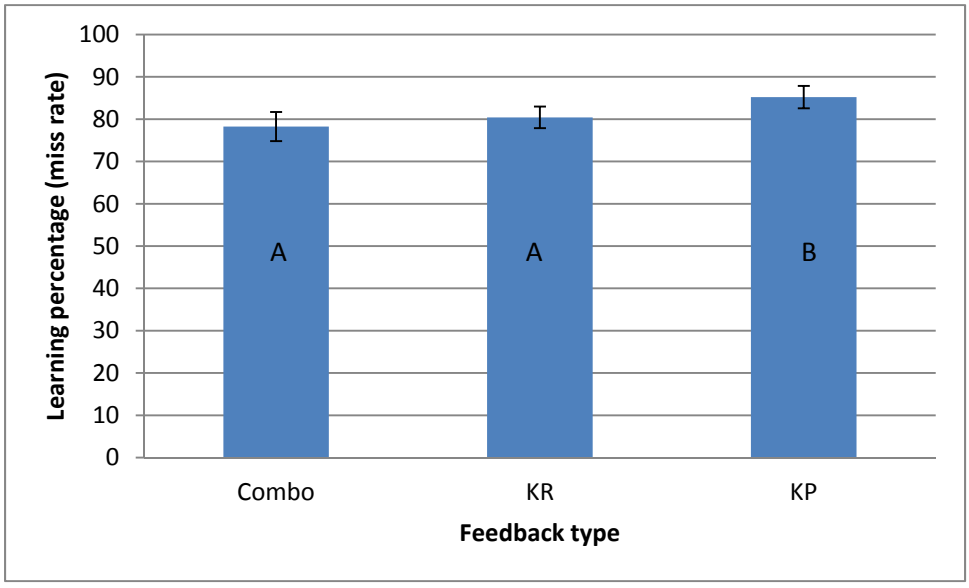

Figure 33. Plot of miss rate learning percentages grouped by feedback type

8.5.2. Learning percentage calculated with Fitts' time

After diagnostics on the data, model residuals revealed a trumpeting trend or expansion in variance across the range of model predictions. The response was transformed using a square root transformation (i.e., sqrt(100-learning percentage)) which successfully resolved the non-

random pattern of the residuals. Results revealed no significant main effect of feedback type ($F(2,32)=0.73$, $p=0.49$) or feedback modality ($F(2,32)=0.28$, $p=0.75$) on Fitts' time learning percentage.

8.5.3. Learning percentage calculated with deviation data

Similar to the previous analysis based on the Fitts' time data, the deviation response was also transformed using a square root transformation (i.e., sqrt(100-learning percentage)). The transformation was successful and results revealed no significant main effect of feedback type ($F(2,32)=0.18$, $p=0.83$) or feedback modality ($F(2,32)=0.66$, $p=0.53$) on deviation learning percentage.

8.5.4. Learning percentage calculated with jerkiness data

Similar to the previous two analyses, the jerkiness response was transformed using a square root transformation (i.e., sqrt(100-learning percentage)) to address a non-constant variance issue among the feedback type and modality settings. Results revealed a marginally significant main effect of feedback modality ($F(2,32)=2.82$, $p=0.07$) on jerkiness learning percentage. Consistent with our hypothesis, post-hoc analysis showed that participants in the auditory and haptic feedback groups produced lower jerkiness learning percentages than those in the visual feedback group (Figure 34). However, no significant main effect of feedback type was found ($F(2,32)=0.35$, $p=0.71$). No interaction effect between feedback type and modality was found ($F(4, 32) = 1.24$, $p = 0.315$).

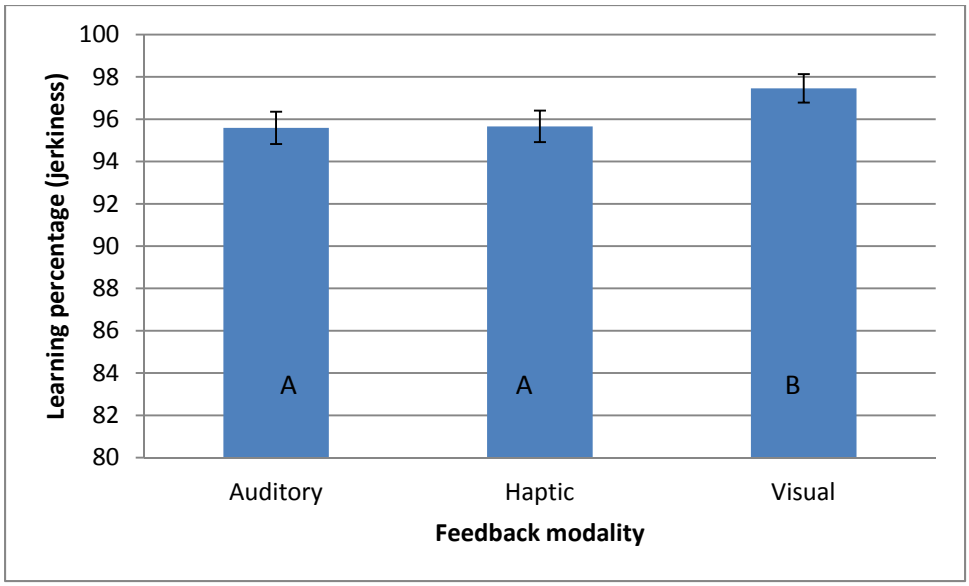

Figure 34. Plot of jerkiness learning percentages grouped by feedback modality

8.6. Additional analysis on the retention score

Based on the previous analysis, the Fitts' time measures the movement speeds, whereas target miss rate measures the movement accuracy. These two responses reflect opposing aspects of the task performance. In order to better derive a response measurement that can encompass both aspects of movement performance, the total movement time (i.e., TMT) for successful Fitts' targets in each trial (i.e., number of hits * Fitts' time) was calculated. The same mixed ANOVA model was applied to TMT during the retention trial.

Results showed that there was a significant main effect of feedback type ($F(2,32)=42.19$, $p<0.0001$) on TMT during retention. According to the post-hoc analysis, participants in the KP group produced significantly lower TMTs than those in the combo group, which in turn had a significantly lower TMT than the KR group (see Figure 35). However, no significant main effect of feedback modality was found ($F(2,32) = 0.84$,

p=0.44). No significant interaction effect between feedback modality and feedback type was found (F(4,32)=1.48, p=0.23).

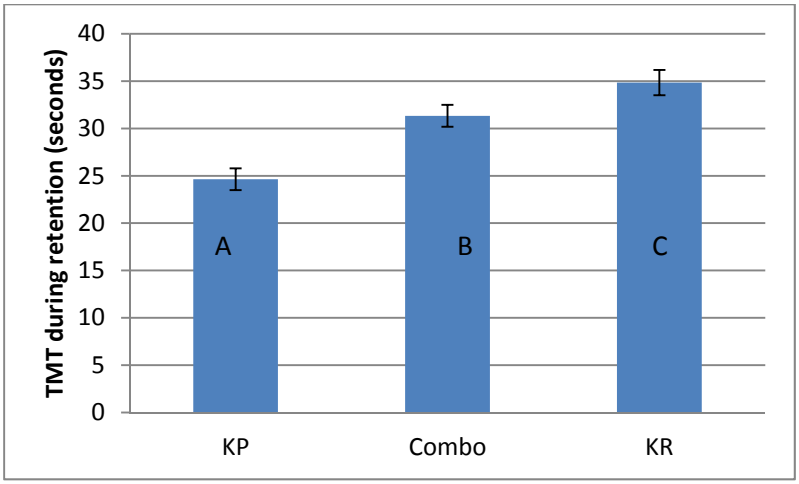

Figure 35. Plot of TMTs in the retention trial grouped by feedback type

8.7. Polynomial Regression analysis

A series of polynomial/quadratic regression analyses was conducted on the retention scores (Y in the model) with intrinsic motivation scores as a predictor (X in the model). The general form of the model was: Y = intercept + Linear term * X + Quadratic term * X^2. The goal of these analyses was to determine whether there was any non-linear relationship between the two responses. Results showed that none of the quadratic terms were significant (see Table 17).

Table 17. Quadratic fitting of the retention score by intrinsic motivation

	Intercept	Linear term	Quadratic term
Fit retention (miss rate) by intrinsic motivation	Estimate = 0.34 p = 0.0006	Estimate = -0.0015 p = 0.56	Estimate = -0.00006 p = 0.80
Fit retention (time) by intrinsic motivation	Estimate = 1100 p = 0.0001	Estimate = -0.775 p = 0.71	Estimate = -0.149 p = 0.49
Fit retention (deviation) by intrinsic motivation	Estimate = 10894 p = 0.0001	Estimate = -44.60 p = 0.42	Estimate = -0.7615 p = 0.196
Fit retention (jerkiness) by intrinsic motivation	Estimate = 122.8 p = 0.0001	Estimate = -0.173 p = 0.448	Estimate = 0.002 p = 0.92

Similar regression analyses were conducted on learning percentage scores (Y in the model) with intrinsic motivation scores as a predictor. For these analysis, samples which showed absolutely no learning were removed (i.e., learning percentage = 100). Results revealed a significant quadratic term in the model of learning percentage (calculated based on path deviations) and human intrinsic motivation (*see* Table 18). The R^2 value for this fit was 0.31 (see Table 19 for R^2 values for various polynomial regression fits). The exact relationship is presented through the plot in Figure 36 ($\sqrt{100 - Y} = 5.73 - 0.065 * X - 0.0088(X - 34.36)^2$);. The Y axis represents the transformed learning percentage score (i.e., sqrt(100-learning percentage)). Lower values on the Y axis corresponded to higher learning percentages, which in turn corresponded to a lower potential for future learning. Consistent with our hypothesis, at the medium level motivation state, participants showed the highest learning potential for reducing path deviation (Figure 36). The path deviation learning percentage data were also fit with higher order terms in the regression model. Table 19 shows the R^2 values for each of the polynomial fits. It appeared that R^2 improved significantly more by adding a quadratic term (to the linear fit) versus adding a cubic term (to a quadratic fit).

This result indicated that there was a non-linear relationship between learning rate (for reducing path deviation) and intrinsic motivation level. The result suggested that both low and high levels of motivation might compromise the learning process for movement control. However, no evidence was found that these motivational states would also degrade task performance learning in terms of movement time and hit accuracy.

Table 18. Quadratic fitting of the learning percentage score by intrinsic motivation

	Intercept	Linear term	Quadratic term
Fit learning percentage (miss rate) by intrinsic motivation	Estimate = 4.07 p = 0.0001	Estimate = 0.01 p = 0.68	Estimate = -0.002 p = 0.45
Fit learning percentage (time) by intrinsic motivation	Estimate = 1.68 p = 0.0001	Estimate = 0.004 p = 0.72	Estimate = -0.002 p = 0.105
Fit learning percentage (deviation) by intrinsic motivation	Estimate = 5.73 p = 0.0001	Estimate = - 0.06 p = 0.0014	Estimate = - 0.008 p = 0.0001
Fit learning percentage (jerkiness) by intrinsic motivation	Estimate = 1.75 p = 0.0015	Estimate = 0.009 p = 0.54	Estimate =0.0006 p = 0.73

Table 19. R^2 values for polynomial regression fits

Term	R^2
1 linear	0.077
2 quadratic	0.312
3 cubic	0.359
4 fourth order term	0.359
5 fifth order term	0.365

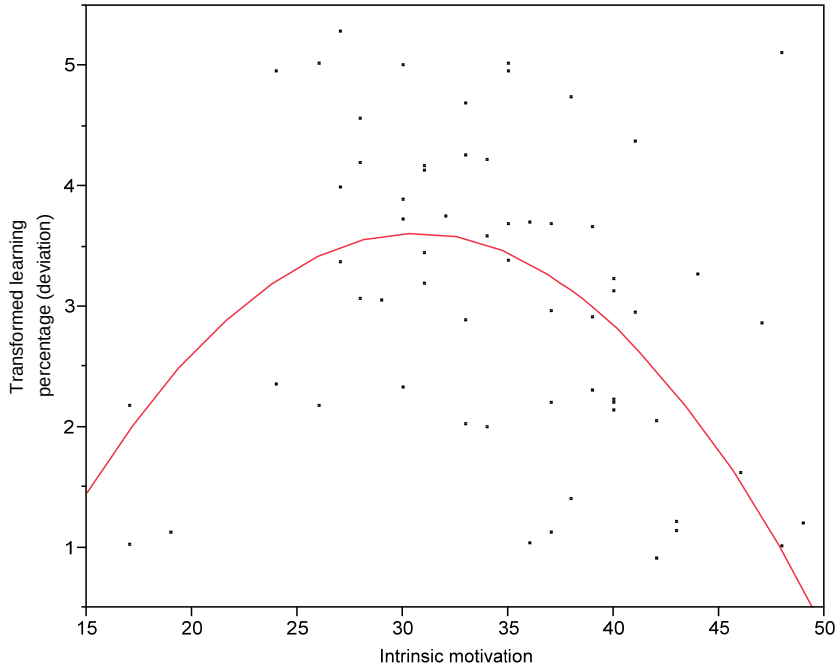

Figure 36. Plot of transformed learning percentage fit by intrinsic motivation

8.8.Correlation analysis on IMI scale scores and learning percentages

Correlation analyses were conducted on the IMI sub scores and learning percentages. Results revealed negative correlations between miss rate learning percentage and perceived competence ($r=-0.361$, $p=0.0018$), as well as between miss rate learning percentage and perceived choice ($r=-0.222$, $p=0.061$). These findings suggested that with higher competence and perceived choice level, trainees could have a higher potential for future learning in terms of reducing target miss rate in the Fitts' task. Given that perceived competence and choice are positive indicators of emotional valence, these results were also related to Lange's theory, suggesting that positive emotional response could have utility for accelerating the learning process.

CHAPTER 9: FULL EXPERIMENT DISCUSSION

9.1. Feedback type and motor skill retention

The KR feedback condition led to better skill retention in terms of movement accuracy than KP, particularly when presented through the auditory modality. However, KP led to better skill retention in terms of movement speed than KR, especially when presented via the haptic or visual modality. These results suggested that there might be a speed-accuracy trade-off associated with discrete movement leaning and skill retention. This could also be attributed to participants not being notified of "task accuracy" outcomes as part of the KR feedback condition. However, such feedback could lead to the sense that achieving accuracy was the only goal for the task (the actual objective was to achieve accuracy and speed simultaneously) and, therefore, participants might have simply focused on hitting more targets during trials. By the same logic, the "miss rate" response likely lacked validity in revealing aspects of skill learning. (Miss rate also revealed a ceiling effect, which introduced sensitivity concerns for the statistical analysis). On the other hand, the derivations on Fitts' time response addressed these drawbacks and the inferences drawn from this response appear to have greater validity for describing skill learning.

A comprehensive task performance measure, the TMT for successful Fitts' targets, was derived to further clarify the effects of feedback type on overall task performance retention. Consistent with our hypothesis, we found KP led to significantly lower TMT for successful Fitts' targets during the retention trial than KR. This suggested that, by considering the human speed-accuracy trade-off strategy into the statistical analysis,

enhanced learning effects of KP were found. Such effects were not mediated by feedback modalities.

The combination of KP and KR, however, did not necessarily result in an additive learning effect. In fact, the effect of the combo feedback on task performance retention was found to be mediated by feedback modality. For example, the auditory combo feedback condition led to the lower Fitts' time than for the auditory KP (or KR) groups during the retention trial. However, participants in the haptic (or visual) combo feedback group actually spent more time on hitting a target during the retention trial than those in the haptic or visual KP groups. It is possible that the combo feedback condition caused information overloading for visual or haptic groups, which in turn affected task learning.

With respect to the learning of movement control kinematics, the combo condition was found to be marginally superior to the individual feedback conditions in terms of jerkiness score during the retention trial. That is, participants in the combo group were less jerky during retention trials than those in the individual feedback groups. This effect was found to be most prominent for the haptic combo feedback condition (see Figure 32). This could be due to the KR feedback reinforcing the learning utility of KP in terms of motor control and jerkiness reduction. Taken together, these findings suggest that either KP, KR or the combo feedback condition can support skill retention. However, the conditions may emphasize different aspects of movement learning.

9.2. Feedback type and motor skill learning rate

With respect to the effects of feedback type on future learning potential (i.e., the complement of the learning percentage), it was found that the KR and combo feedback conditions led to

marginally steeper learning curves for reducing target miss rate than the KP condition during the training period. These results were consistent with the previous finding that KR resulted in a lower miss rate than KP in the retention trial. Both results could be due to participants in the KR group being biased by the feedback content and a focus on improving the accuracy aspect of task performance.

In general, although KR led to a higher learning rate for achieving Fitts' task accuracy (possibly due to the experimental feedback configuration), KP resulted in a better performance score in terms of Fitts' time or TMT during the retention trial. These results represent strong empirical complements to Cirstea and Levin's (2007) study, in which they assessed the effects of auditory KP and visual KR on skill retention. Their results showed that auditory KP resulted in better joint coordination and larger movement ranges in retention trials as compared with visual KR. However, they failed to provide any comparisons of learning rates between KR and KP. As a consequence, meta-data analysis and cross-study comparisons could not be conducted.

9.3. Feedback type and motor skill learning

Compared to the KR group, participants in the KP group had to process information in more detail during the training period due to the nature of the two feedback types. KR is task-outcome based information, whereas KP is movement-process based information. Participants in the KP group received feedback, allocated attention to the state of the cursor (or limb), applied a movement strategy in approaching the target goal, performed a decision making process, and further executed movement responses. Participants in the KR group could, however, used a simplified information processing strategy. Therefore, a steeper

learning rate for the KR group was observed. The more complex internal information processing associated with KP feedback was expected to lead to more accurate motor program formation, which in turn directly affects skill retention. Results confirmed this research expectation. It was found that KP led to increased skill retention (in terms of Fitts' time and TMT) than the KR condition. As a consequence, the proposed HIP perspective on motor learning was supported.

Based on the survey results, almost 80% of the participants (i.e., 19 out of 24) preferred the KR feedback, and thought this type of information could support learning and performance more than the KP feedback. They liked the fact that the system provided some sort of notification when they hit a target and they felt that it motivated task performance. Participants did not like the KP feedback for various reasons. Under the visual KP condition, for example, some participants commented that the blinking red cursor (with path deviation) was distracting to performance. Others simply ignored the blinking cursor and tried to focus on hitting the targets. One participant commented that such information (i.e., visual KP) might be more efficient for task learning if it was provided after the test trial via a video replay. This study only investigated concurrent forms of feedback and not retrospective KP or KR. With respect to auditory KP, most participants thought the tone during path deviation was annoying, irritating, and could increase stress level. Subjects tried to avoid the tone by performing more accurate movement trajectories. Therefore, this condition actually substantially increased cursor control accuracy. With respect to the haptic KP condition, participants also found the Falcon vibration during cursor control to be distracting and to be

inefficient relative to KR feedback. Some commented that the haptic KP feedback condition might work for motion learning, but only when subjects paid attention to it.

Participant preferences for individual feedback type also developed under the combo condition. Participants in the combo group could easily distinguish between the two feedback types. They preferred KR and tended to pay more attention to this information during tests. There was no evidence that participants preferred the combo feedback condition more than the individual feedback conditions. In fact, some participants expressed concerns that the KP feedback might subtract from the learning utility of KR in the combo condition.

Only five out of 24 participants found both the KP and KR conditions to be helpful for skill learning and motivation. One subject thought the haptic KP was “cool” and could successfully reinforced movement trajectory learning. Another one initially commented that the background tone (i.e., auditory KP) was distracting and contributed to his lower accuracy rate. However, he later commented that the feedback motivated him to follow the projected path towards the target. With respect to the visual KP condition, one participant said that it helped him maintain awareness of his breathing and it prompted him to slow down to discretely hit each target.

In general, it appeared that the statistical analysis results corresponded with the survey results. For example, survey results showed that participants preferred outcome notification feedback (KR), and tended to pay more attention to such cues. This preference may explain the finding of a steeper learning curve for reducing target miss rate during KR training trials. In addition, the KP feedback was found to support task performance retention more than KR feedback, even though KP was regarded as annoying and “distractive to

learning and performance" by subjects. This finding and observations are consistent with the fact that motor learning is an internal process and trainees might not be aware of the process during training.

9.4. Feedback modality and motor skill learning

Consistent with our hypothesis, the auditory and haptic modalities led to better retention scores than the visual modality. However, this effect was mediated by the feedback types and was only statistically prominent under the combo feedback condition. For example, the auditory combo feedback resulted in significantly shorter Fitts' time and fewer path deviations than the visual or haptic combo conditions (refer to Figure 27). The haptic combo feedback was also found to lead to significantly less jerkiness than the visual or auditory combo feedback conditions (refer to Figure 32). No main effects of feedback modality on skill retention were found for the individual KP or KR groups. This lack of effect could be due to the individual KP or KR conditions not being cognitively complex enough to lead to strategy differences in human information processing. In other words, the retention utility of the auditory or haptic modality was more easily revealed through complex information cues.

In addition to the findings on retention scores, auditory and haptic cues were found to lead to higher learning rates for reducing movement jerkiness than visual groups. This main effect was statistically marginal and was not mediated by feedback type. However, the result suggested that learning curve analysis might be more sensitive for revealing the learning utility of auditory or hatpic cues than retention analysis. Taken together, these findings provide evidence that there is a role of feedback modality on motor skill learning and retention.

9.5. The learning effects of feedback modality: The theory behind the observations

Based on the prior literature, a key difference among the visual, auditory and haptic feedback groups can be found in the length of stimulus retention in the STSS. Wickens (2000) said that iconic sensory cues remain in the STSS for less than 1 second, whereas echoic or kinesthetic sensory cues could last for several seconds. Cowan (1988) revised the pipeline HIP model and theorized that the STSS includes two distinct phases. The first phase of STSS retains unanalyzed information for approximately 200 ms in duration, whereas the second phase of STSS retains partially "processed" stimuli for approximately several seconds. According to Cowan, the retention capability of the first phase of the STSS does not differ a lot across modalities (it usually prolongs the sensation for several hundred milliseconds). However, the STSS time in the second phase differs dramatically across modalities. For example, humans can recall unattended near-threshold auditory or kinesthetic stimuli up to 10 seconds after presentation. However, storage of partially processed iconic stimuli (i.e., codes being used for pattern recognition) begins to fade after 0.5s and continues up to 2s.

Such differences in STSS retention time might mediate the degree of information exchange between the STSS and LTM among modalities with stimulus feature encoding being more common for auditory or kinesthetic cues than visual. In fact, Cowan (1998) reported that pattern matching of unattended contents of the STSS could be successful for up to 8 seconds for iconic cues, and 20 seconds for auditory and kinesthetic cues. These retention duration differences lead to further differences in motor memory generation (regarded as a key process in learning) in the sense that the pattern of desired muscular innervations may be stored more effectively in LTM with longer retention intervals.

The learning advantage of the haptic cues over visual cues can also be explained with Cowan's habituation hypothesis of selective attention (Cowan, 1988). This hypothesis states that physically unchanged stimuli are commonly habituated and do not elicit attention, whereas novel stimuli are more likely to enter the focus of attention through voluntary processing. Attentive processing of "novel" stimuli results in a more elaborate encoding of information, which is critical for memory retrieval and episodic storage. In the current experimental setup, visual cues from a screen were less novel than kinesthetic cues felt on the haptic control device and, therefore, were more likely to be habituated during task performance without internal processing and encoding. Based on Cowan's theory, visual cues were likely to be automatically processed and this contributed to procedural knowledge stores but not episodic memories. Haptic cues were more likely to undergo conscious processing (especially in the initial trials), which required attention, and information entered the state of subject awareness. This processing resulted in episodic memory formation and was beneficial for motor learning.

On this basis, it seems there are two main HIP theories that could explain the modality differences in motor learning. The first one is the STSS time difference across sensory cues. That is, haptic cues can be retained in the STSS and STM longer than visual cues. As a consequence, humans will simply have more time for encoding and processing haptic cues than visual cues. The second theory is that humans tend to apply habituation strategies when allocating attention to information cues. Novel cues (e.g., force cues from a haptic device) are more likely to be processed consciously (instead of being habituated and processed automatically) and this contributes to higher levels of motor learning. In the

current study, haptic cues might be dishabituated in the first few trials but the learning effect was transient.

There was also support for the above explanations from the subject survey. For example, most participants in the visual KP group reported that they did not pay attention to the flashing cursor during testing. However, participants in the haptic KP group reported that they needed to pay more attention to the vibration cues and to adjust their movement trajectory to avoid the vibration. These comments suggested that subjects in the visual KP group internally applied a habituation strategy to the flashing cursor cue, whereas those in the haptic KP group applied a conscious processing strategy for the vibration cues. As a consequence, the haptic KP group achieved greater learning outcomes than the visual KP group.

9.6. Sensory feedback and motivation

Consistent with hypothesis, the KR feedback led to significantly higher intrinsic motivation than the KP feedback. This result complements that obtained by Colombo et al. (2007). They found a combination of KP and KR feedback to result in higher scores for the interest, usefulness and importance subscales of the IMI and lower values for the tension and pain subscales, as compared to a control (no feedback) group. The findings of the present study provide additional evidence to support the hypothesis that the underlying motivating mechanisms between KP and KR are quite different. More specifically, motivational effects of KR have been found to be a function of goals and knowledge of performance relative to criteria (consistent with Locke, Cartledge & Koeppel [1968]'s study), whereas motivating effects of KP are more likely due to subject interests in the nature of cues. It was expected

that KR feedback was more likely to trigger the process of self determination (Ryan and Deci, 2000) than KP feedback (note: the self determination process has been theorized to be the key component activating motivational responses). Such expectation was also verified from the survey data. For example, most subjects reported being more motivated in the KR condition. They attributed high level motivation to the fact that they felt more and more confident with the outcome feedback and they wanted to beat their previous scores in the next trial. These perceptions of competence and autonomy in turn served as energizers for self-motivated behavior for task learning.

Haptic cues also led to higher intrinsic motivation states than visual or auditory cues. This was consistent with the Lecuyer et al. (2002) study in which haptic cues were found to be more pleasant and more intriguing than visual/auditory cues in a VR-based industrial insertion task. The present subject survey also confirmed this point. For example, participants reported that haptic cues were “cool” and they were also more willing to choose training with haptic cues than with visual or auditory cues.

9.7.Motivation and learning

The current study found that a medium level motivational state led to steeper learning rates for reducing path deviation than lower or higher motivational states. This is similar to the arousal-performance relationship from Yerkes-Dodson Law, in which human performance was found to be worse in lower or higher arousal states due to boredom or loss of peripheral information, respectively. However, no correlation was found (in the current study) between intrinsic motivation and learning rates for improving task time or hit accuracy (see the first two rows in Table 18; only the intercepts were significant). This lack of correlation suggests

that extrinsic motivation, as in rehabilitation settings in which researchers or therapists coach patients, might promote motor control learning instead of simply providing the subject with information on task performance (i.e., higher scores or shorter times).

9.8. A list of feedback design guidelines

Based on the research findings and the discussions in the previous sections, a list of feedback design recommendations (R1 – R8) is proposed, as follows:

R1. To support skill retention of task performance in general (e.g., considering both speed and accuracy), KP should be delivered, preferably through the haptic or visual modality.

R2. To train for a specific aspect of task performance (e.g., accuracy) only, KR can be delivered to drive trainees' attention to the particular task element. This helps accelerate the learning process for the task element. It also ensures greater retention for the task element.

R3. A combination of KP and KR through the same modality is not effective for producing a positive additive learning effect for task performance.

R4. To support skill retention in jerkiness control, a combination of KP and KR feedback should be delivered instead of individual KP or KR feedback, preferably through the haptic modality.

R5. With the existence of multiple information cues (e.g., a combo feedback condition), haptic or auditory feedback should be used if the learning objective is skill retention in terms of speed and deviation.

R6. With the existence of multiple information cues (e.g., a combo feedback condition), haptic cues should be used if the learning objective is skill retention in terms of jerkiness.

R7. To sustain intrinsic motivation, task outcome related feedback (e.g., a KR or combo feedback condition) should be delivered through the haptic modality.

R8. A medium level motivational state is helpful for increasing learning rates and improving motor control accuracy, particularly when using the haptic modality.

CHAPTER 10: RESEARCH APPLICATIONS

10.1. Industry assembly training

The research findings presented here may serve as feedback design guidelines for VR-based industrial assembly training systems. For example, Gutiérrez et al. (2010) designed and developed a multimodal virtual training system for skill transfer in industrial maintenance and assembly tasks (see Figure 37). This system uses a haptic glove interface to track the motion of a trainee's dominant hand and to simulate physical interactions within the virtual world. The trainee's hand is rendered and displayed on the screen as a red ball (i.e., a form of KP feedback in terms of user movement state). The mechanical parts are rendered as solid, but they can be switched to a transparent mode, through which trainees have a clear view of the internal state of the machine (i.e., a form of KP feedback). In addition to these features, a collision detection mechanism is included in the system. This provides knowledge of results on the assembly outcome. The Gutiérrez et al. system is also capable of restraining a trainee's hand motion along a visual path through constraint forces (haptic feedback delivered via a device). This is also a form of KP feedback that could be extremely helpful when training for assembly of delicate machine components. With these cues, trainees could accurately learn movement paths, preventing accidental damage of delicate parts due to undesirable movements in real task performance.

Collectively, the Gutiérrez et al. (2010) training system employed a combination of visual KP, haptic KP and haptic KR feedback to support assembly task learning and trainee motivation. To improve this system, auditory cues could be added to verbally inform a trainee of his hand position in real time. Such cues would be helpful for increasing trainee

awareness of hand position when s(he) cannot see the proxy of his/her hand in the VR (i.e., the red ball) clearly due to shaded mechanical parts. In addition to this, visual notification of successful sub-assembly (e.g., highlighting/flashing of the assembled parts for several seconds) would be helpful to sustain trainee motivation. With respect to the existing haptic KP feedback (i.e., restraining the hand motion along a path), it could be replaced by a less restrictive form of haptic KP in the later stage of learning. For example, it might be better to allow free hand motion with resistive forces occurring only when moving and inserting a part along a misaligned trajectory.

With the help of VR technology, it would not be difficult to integrate various forms of multimodal sensory feedback during the assembly training processes. However, in real-world assembly learning scenarios, such concurrent multimodal feedback might not be possible due to various constraints (e.g., lack of trainers and a limited amount of training time). If only one type of feedback could be provided during real-world assembly training, based on the current research findings, it is recommended that haptic KR be included in the early stage of the training to sustain task motivation and future learning. Augmented KP feedback, preferably via the visual modality, should be gradually included after the initial learning stage to support finer motor control and skill retention. Auditory notifications of overall task outcomes could also be included to reinforce knowledge of outcomes and motivation at the end of the task.

Figure 37. Virtual training system for assembly tasks from Gutiérrez et al. (2010)

10.2. Rehabilitation training

The current research findings could also be applied to the design (or redesign) of current rehabilitation systems. For example, the Gentle/s (Loureiro, et al., 2003) employs a haptic device for training reaching tasks for stroke patients (Figure 38). Currently, this system integrates three types of haptic control training including: (1) a patient passive mode (i.e., the system guides patient movement), (2) a patient active mode (i.e., patient self-control of movement), and (3) a patient active and assisted mode (i.e., the assistive device starts moving as soon as the patient initiates a movement). Although all the training modes provide some haptic cues to patients, none of them represent KP feedback (i.e., knowledge of movement state and limb/hand position relative to a goal). In the future, it would be helpful to integrate (haptic) KP feedback in this system. For example, if the user deviates from a predefined motion path, the haptic interface could automatically guide his/her hand back to the original path. Another possible solution might be to include some sort of haptic penalty (e.g., resistive

force to make the task more difficult) with path deviation. Visual KP feedback could also be included to support multi-modal information processing. For example, a user's hand position could be projected on the virtual background through an active virtual line. The position of the line would indicate the X-Y position of the hand, whereas the length of the line would indicate the depth of the hand. With these cues, patients could obtain a better understanding of their hand position in the virtual world. Based on the results of the present study, these redesign proposals would be expected to support skill retention and learning.

Figure 38. Virtual rehabilitation system from Loureiro et al. (2003)

10.3. Robotic-assisted surgery training

The findings of this research could also be applied to healthcare surgery training scenarios. For example, in the surgery training system developed by Morris et al. (2007), three different types of augmented feedback are provided (see Figure 39). The first one includes instantaneous haptic feedback on the target force level (i.e., the haptic device applies the embedded force pattern perpendicular to the movement plane; the user's goal is to keep the

device in the movement plane). The second one includes instantaneous visual feedback on the target force (i.e., a green rectangle). The third one includes both visual and haptic cues, plus a green bar showing the current user applied force. The third form of feedback actually represents a combination of KP and KR in visual form, as well as haptic KP along the Z axis. Consistent with the present results, Morris et al. (2007) found that this third feedback condition led to the greatest learning outcomes among all three conditions. However, the Morris et al. (2007) system did not provide additional feedback support for ensuring accurate trajectory movement (i.e., how accurate a user follows a predefined path). This is an important aspect of training for surgery. Based on the present research, the visual KP in the existing system should be removed since it could lead to additional development cost for feedback system with no additive benefit over KP or KR. Instead, force constraints (with variable thresholds based on the level of user experience) should be included in the X-Y motion plane to better reinforce motor control movement learning.

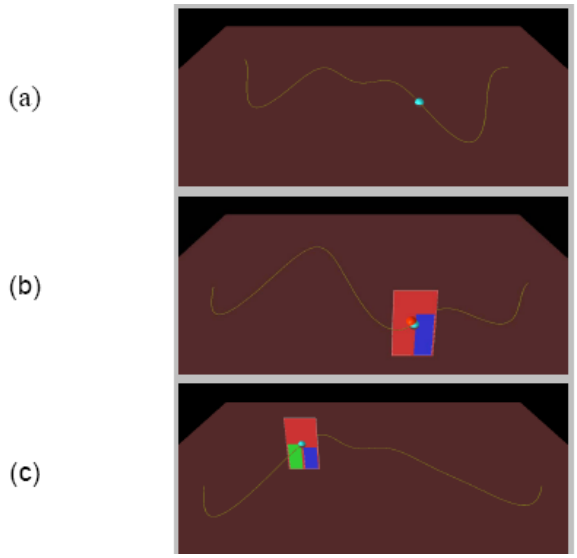

Figure 39. Virtual training system for surgery operations from Morris et al. (2007)

CHAPTER 11: CONCLUSIONS

In conclusion, an empirical study assessing how feedback type and modality influence skill learning and human motivation was conducted. A human information processing perspective of manual motor skill learning was adopted and used as a basis for formalizing research hypotheses. Feedback design guidelines were proposed based on experimental results and application examples were described. The following sections identify the limitations of this work and future research directions.

11.1. Research limitations

In this study, KP feedback in the Fitts' task was delivered based on negative task events (i.e., motion path deviations), whereas KR was delivered based on positive events (i.e., a target hit). These forms of feedback encoding were used to ensure usability for task performance. More specifically, if KR was also delivered on the negative events, it would severely compromise the usability of the training system/task, which in turn would inhibit learning. However, such a feedback configuration might lead to differences in human motivational responses. Based on the final interview results, subjects in the KR group reported that they were motivated by how well (or bad) they performed in the task. Subjects in the KP group, on the other hand, reported that they concentrated more on adjusting movement trajectory during the test. These comments were consistent with the original feedback design concepts (i.e., KR directs user attention on task outcomes, whereas KP directs user attention on movement processes/states). In fact, none of the participants reported that they thought KR was more motivating than KP simply because they received "good" outcome feedback in the KR condition. Some subjects were even disappointed with "extremely low" hit rates they

received at the end of test trials. These observations indicate that even though KR is designed to be delivered on positive events, users might not perceive it as being positive in a similar manner. In fact, most participants were not even aware of the negative/positive aspects of the feedback they received.

Another potential limitation of the present study concerns the retention interval length. The current 5-minute retention interval was chosen based on pilot study observations. Although the rest duration used in the full experiment was almost five times longer than the length of a test, there was no guarantee that skill loss would occur for all the participants within such a short period of time (due to individual differences in memory and learnability). Therefore, the initial objective was to use a retention interval length as long as possible, provided that the total experimental length for one participant would be within 1 hour. In the future, the present study could be expanded to include multiple training sessions with a significantly longer rest period (e.g., one day or one night). Such an approach might provide for a better understanding of human internal processes of skill retention.

A final limitation of the present work relates to the polynomial regression results. Although the quadratic terms were significant in the polynomial regression models, the goodness of fit statistics (i.e., R^2 values) were low (0.3). To address this limitation, it is recommended that additional experimental controls be applied (e.g., test environment configuration, participant performance reminders) or that additional predictor variables (e.g., gender and age) be included in the model.

11.2. Future work

In the current study, participants completed the motor training task with their left (non-dominant) hand only. It would be interesting to expand the current research to include bimanual motor skill training. One option would be to study how sensory feedback affects motor skill learning/training in terms of bimanual coordination in a rehabilitation setting. In addition to this, investigation of multimodal feedback and the effects on motor skill retention would be a future research topic. For example, auditory KR and haptic KP could be combined as one feedback condition and the learning utility of the condition could be empirically assessed. Participants in the current used their non-dominant hand during the training to simulate certain motor impairment similar to disabled patients. Future experiments should also be conducted on trainees who are challenged in terms of cognitive processing (e.g., memory and decision making issues). Related to this, the current study focused only on the associative stage of the learning process. That is, the procedure rules for the current motor training task were trivial and participants started almost immediately from the motor control aspects of learning. In the future, it would also be interesting to study the effects of KP and KR on the first stage of the learning process (i.e., the cognitive stage). This approach would be directly applicable to industrial assembly learning tasks, which require not only delicate motor control for moving components, but also a quick and clear understanding of task procedures.

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APPENDICES

Appendix A

Survey questions

1. How do you like the first feedback training condition? Do you think such type of feedback support learning? Do you think the feedback support task performance? Why and why not?

2. How do you like the second feedback training condition? Do you think such type of feedback support learning? Do you think the feedback support task performance? Why and why not?

3. How do you like the third feedback training condition? Do you think such type of feedback support learning? Do you think the feedback support task performance? Why and why not?

Appendix B

North Carolina State University
INFORMED CONSENT FORM for RESEARCH

Title of Study: Assessing the feedback effects on motor learning and human motivation

Principal Investigator: Biwen Zhu Faculty Sponsor (if applicable): David B. Kaber

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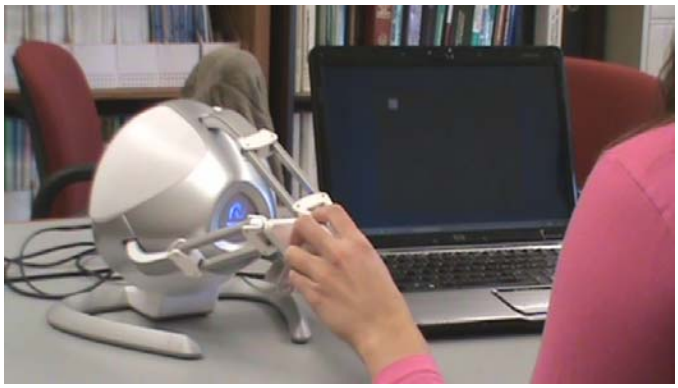
What are some general things you should know about research studies?

You are being asked to take part in a research study. Your participation in this study is voluntary. You have the right to be a part of this study, to choose not to participate or to stop participating at any time without penalty. The purpose of this research study is to gain a better understanding of how various forms of sensory feedback may influence motor skill learning processes. You are not guaranteed any personal benefits from being in this study. Research studies like this may also pose risks to those that participate. In this consent form you will find specific details about the research in which you are being asked to participate. If you do not understand something in this form it is your right to ask the researcher for clarification or more information. A copy of this consent form will be provided to you. If at any time you have questions about your participation, do not hesitate to contact the researcher(s) named above.

What is the purpose of this study?

The purpose of this study is to investigate the effects of sensory feedback on motor skill learning and human motivation in a computer-based training task. In this study, you will be asked to perform a series of "Fitts' (discrete movement) tasks". The goal of "Fitts' task" is to detect a target on a computer screen and execute a click on the target as quickly and as accurately as possible using a haptic stylus.



What will happen if you take part in the study?

If you agree to participate in this study, you will be asked to:

1. Read and sign this consent form, once you understand the research and agree to participate
2. Fill out a background survey
3. Complete a device training session
    a. You will be asked to "perform a basic Windows File Moving Task" using the Novint Falcon controller with your dominant hand.
4. Researchers will provide a briefing of the formal training task
5. Complete three training conditions
    a. Complete 5 trials for the first condition
    b. Take a 10 minute rest

i. During the rest, you will complete a motivation questionnaire

c. Complete one additional trial for the specific test condition

d. Continue for the next feedback condition until all the conditions are completed

6. Complete a final survey

The study will be conducted in a separate conference room located on the fourth floor of Daniel Hall, NCSU. The study will last approximately 1 hour.

Risks

A potential risk of hand/wrist fatigue may be involved during training with the haptic device. Participants with current or chronic back, shoulder, neck, or wrist pain will be excluded from this study. We will provide sufficient rest periods (i.e., 10 minutes) after each block of six training trials.

Benefits

There are no direct benefits to you from this research.

Confidentiality

The information in the study records will be kept confidential to the full extent allowed by law. Data will be stored securely in the Cognitive Ergonomics Lab in the NC State Department of Industrial and Systems Engineering. No reference will be made in oral or written reports which could link you to the study. A background survey will collect identifying information such as your name. Other data will include your gender and age and will be used for demographic statistics. A code number will be matched to your name and a master list of codes for all subjects will be kept separately from all other survey and response data collected as part of the experiment. This code list and all other data will be destroyed at the close of the study.

Compensation

For participating in this study you will receive $15 compensation. If you withdraw from the study prior to its completion, you will receive $5 partial compensation. You will receive an additional $15 compensation if your task performance is in the top 3 among all subjects.

Contact

If you have questions at any time about the study or the procedures, you may contact the researcher, Biwen Zhu, at 458 Daniels Hall, NC State University main campus, or [9199955616]. If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact Deb Paxton, Regulatory Compliance Administrator, Box 7514, NCSU Campus (919/515-4514).

Consent To Participate

"I have read and understand the above information. I have received a copy of this form. I agree to participate in this study with the understanding that I may choose not to participate or to stop participating at any time without penalty or loss of benefits to which I am otherwise entitled."

Subject's signature_____ **Date** _____

Investigator's signature_____ **Date** _____

Appendix C

THE POST-EXPERIMENTAL INTRINSIC MOTIVATION INVENTORY

Subject Name: _____ Trial Number: 1

For each of the following statements, please indicate how true it is for you, using the following scale:

1 2 3 4 5 6 7

not at all true somewhat true very true

- ☐ 1. While I was working on the task I was thinking about how much I enjoyed it.
- ☐ 2. I did not feel at all nervous about doing the task.
- ☐ 3. I felt that it was my choice to do the task.
- ☐ 4. I think I am pretty good at this task.
- ☐ 5. I found the task very interesting.
- ☐ 6. I felt tense while doing the task.
- ☐ 7. I think I did pretty well at this activity, compared to other students.
- ☐ 8. Doing the task was fun.
- ☐ 9. I felt relaxed while doing the task.
- ☐ 10. I enjoyed doing the task very much.
- ☐ 11. I didn't really have a choice about doing the task.
- ☐ 12. I am satisfied with my performance at this task.
- ☐ 13. I was anxious while doing the task.
- ☐ 14. I thought the task was very boring.
- ☐ 15. I felt like I was doing what I wanted to do while I was working on the task.
- ☐ 16. I felt pretty skilled at this task.
- ☐ 17. I thought the task was very interesting.
- ☐ 18. I felt pressured while doing the task.
- ☐ 19. I felt like I had to do the task.
- ☐ 20. I would describe the task as very enjoyable.
- ☐ 21. I did the task because I had no choice.
- ☐ 22. After working at this task for awhile, I felt pretty competent.

Submit

Appendix D

Edinburgh Handedness Inventory

Please indicate your preference in the use of hands in the following activities *by putting + in the appropriate column*. Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, *put + +*. If in any case you are indifferent, *put + in both columns*.

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all the questions, and only leave a blank if you have no experience at all in the object or task.

		LEFT	RIGHT
1	Writing		
2	Drawing		
3	Throwing		
4	Scissors		
5	Toothbrush		
6	Knife (without fork)		
7	Spoon		
8	Broom (upper hand)		
9	Striking Match (match)		
10	Opening box (lid)		
i	Which foot do you prefer to kick with?		
ii	Which eye do you use when using only one?		

L.Q		Leave these spaces blank	DECILE	