

The effects of manipulated augmented sensory feedback on  
error detection when using a touch screen.

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## **DEDICATION**

For my family, and my Superman... more than ever

## **Abstract**

The purpose of the present study was to determine which augmented sensory modality would best develop subjective error-detection capabilities of learners performing a spatial-temporal task when using a touch screen monitor. Participants were required to learn a 5-digit key-pressing task in a goal time of 2550 ms over 100 acquisition trials on a touch screen. Participants were randomized into 1 of 4 groups: 1) visual-feedback (colour change of button when selected), 2) auditory-feedback (click sound when button was selected), 3) visual-auditory feedback (both colour change and click sound when button was selected), and 4) no-feedback (no colour change or click sound when button was selected). Following each trial, participants were required to provide a subjective estimate regarding their performance time in relation to the actual time it took for them complete the 5-digit sequence. A no-KR retention test was conducted approximately 24-hours after the last completed acquisition trial. Results showed that practicing a timing task on a touch screen augmented with both visual and auditory information may have differentially impacted motor skill acquisition such that removal of one or both sources of augmented feedback did not result in a severe detriment to timing performance or error detection capabilities of the learner. The present study reflects the importance of multimodal augmented feedback conditions to maximize cognitive abilities for developing a stronger motor memory for subjective error-detection and correction capabilities.

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## CHAPTER 1: REVIEW OF LITERATURE

### 1.1 Motor Skills and Motor Learning

Motor skills are essential to complete everyday tasks such as walking, lifting objects, and signing a cheque. Schmidt and Lee (2013) highlight several continuums with anchors on each end that classify a motor skill. One distinct characteristic of a motor skill is the size of the primary musculature used to complete the movement. A *gross* motor skill requires learners to use larger muscles to complete the movement (e.g., walking) whereas a *fine* motor skill requires smaller muscles to be used (e.g., typing a word on a keyboard). Motor skills can also be classified as *discrete*, *continuous*, or *serial* skills (Schmidt & Lee, 2013). Discrete skills have a distinct beginning and end (e.g., flipping on a light switch). Continuous skills have an arbitrary beginning and end (e.g., walking), and serial skills combine a sequence of discrete movements together (e.g., changing gears in a standard car). A motor skill can be further classified into *open* or *closed*. An open motor skill is one that is performed in an unpredictable environment (Schmidt & Lee, 2013) such as a batter attempting to hit a pitch thrown by a pitcher. A closed motor skill involves movements that are performed in predictable environments (Schmidt & Lee, 2013) such as a batter attempting to hit a ball from a tee.

One common motor skill often performed on a daily basis is a button push. Whether it is on a keyboard, telephone, or an ATM keypad, button pushing has become a ubiquitous skill quintessential for everyday life. Smaller buttons may require more precise movements (e.g., one finger) to depress the button, thus the *action* of the button push may be classified as a fine motor skill. Often times, a button push has a distinct beginning and end (e.g., pushing the power button from on to off) therefore it may be

classified as a discrete motor task. However when a sequence of button pushes must be made (e.g., entering a phone number), it may be classified as a serial motor task. If environmental conditions are unpredictable (i.e., walking in a busy hallways while typing in a phone number), it may be considered an open motor skill. If environmental conditions are predictable (i.e., sitting and typing in an empty room), it may be considered a closed skill. For the purpose of this study, a key-pressing task on a touch screen device (TSD) in a quiet laboratory was used. Therefore, this task was classified as a fine, serial motor task performed in a closed environment. Furthermore, the level of complexity can be determined by *Fitts Law* (1954). This examines the relationship between movement time (MT) and task difficulty (i.e., index of difficulty [ID]).

Specifically, ID is expressed in terms of the distance between the centre of the two targets (i.e., amplitude [A]) and the target size (i.e., width [W]). The ID of a movement task is expressed as:  $ID = \log_2(2A/W)$ . From this study,  $A = 23\text{mm}$  and  $W = 20\text{mm}$ . Based on Fitts Law (1954), the ID for this button pushing task is 1.20 bits. ID is quantified as *bits* of data based on the *Information theory* ( $\log_2$  is the binary logarithm equivalent to the 1s and 0s used in modern computers to represent information; Fitts, 1954). From 1 bit of information, the only possible states are 0 or 1. Therefore the ID for this to-be used task is very low as participants will not have to process large bits of information.

The acquisition of a motor skill requires a change in internal processes as a direct result of physical practice leading to a relatively permanent change in the ability to perform the task (Schmidt & Lee, 2013). The goal of practice is to increase the strength of these internal processes and to refine movements towards the movement goal (Kantak & Winstein, 2012; Schmidt & Lee, 2013). A recent review conducted by Kantak and

Winstein (2012) highlights the neurological changes that occur during motor learning. It is understood motor learning cannot be directly observed since it involves complex neural and cognitive processes (Kantak & Winstein, 2012). During the acquisition of a motor skill, the *encoding phase* (i.e., online process) occurs during physical practice, resulting in the development of a motor memory of the to-be-learned task. This encoding phase allows for the processing of task-related information (e.g., task goal, movement outcome) to be generated primarily in the frontal cortex, striatum and cerebellum (for review see Doyon et al., 2009). Following physical practice, a process termed *consolidation* (i.e., offline process) occurs (Kantak & Winstein, 2012). The motor memories developed during the encoding phase are strengthened during a pre-determined time without physical practice (Kantak & Winstein, 2012). Motor learning is then inferred by examining the changes in motor performance over time (i.e., 24 hours following practice, Kantak & Winstein, 2012) when motor memory consolidation has occurred (Cahill, McGaugh, & Weinberger, 2001; Kantak & Winstein, 2012).

During acquisition, the performance of the learner may indicate superior improvements from the beginning to the end of practice. However, caution should be used when interpreting these performance gains as learning, as these behaviours may not persist over time (Guadagnoli & Lee, 2004; Schmidt & Lee, 2013). Under certain practice conditions, a learner may demonstrate superior performance suggesting learning has occurred. However, when the learner is asked to reproduce the same movement but under different conditions from practice, there may be a decrease in performance. For example, a learner is asked to complete 100 trials of a key-pressing sequence of “2-4-7-9-1” in an overall movement goal time of 2550 ms. If the timing accuracy is calculated

using constant error (CE), a decrease of CE over time would indicate an increase in performance (e.g., learners are getting better at the task). However, when the learner is asked to reproduce this movement (e.g., overall movement time goal of 2550 ms) approximately 1 day following practice, CE may not be similar to CE values from the end of practice. Although the learner appeared to “learn” the task during practice, the decrement in performance from the end of practice to the second day reflects the *performance-learning paradox*. The spatial aspect of the task (i.e., the key pressing) may have been learned but the temporal aspect (i.e., overall movement goal time) may not have been learned. The performance-learning paradox differentiates motor behaviour resulting from practice conditions (i.e., motor performance) and the resilience of behaviour over time (i.e., motor learning; Katak & Winstein, 2012). To infer learning of the motor skill, retention tests are conducted (Russell & Newell, 2007). *Delayed retention tests* (at least 24 hours following acquisition; e.g., Katak & Winstein, 2012; Lai & Shea, 1999; Liu & Wrisberg, 1997; Patterson, McRae, & Lai, 2014) are a practice context whereby all groups perform the task under the same experimental condition (e.g., no feedback), thus allowing for equivalent comparisons between experimental conditions. Delayed retention tests assess the relatively permanent effects associated with practice of the motor task in a specific context. Typically performed twenty-four hours following the end of practice, a delayed retention test allows consolidation to occur, as the motor memory is strengthened in the absence of physical practice (Katak & Winstein, 2012). Additionally, the consolidation period allows for any temporary performance-gaining (e.g., guidance from feedback) or performance-deteriorating (e.g., fatigue) effects to dissipate (Russell & Newell, 2007; Salmoni, Schmidt, & Walter, 1984; Schmidt & Lee,

2013). Performance behaviours observed at the end of acquisition may or may not persist following the consolidation period and into the retention test. For example, Liu and Wrisberg (1997) investigated feedback (knowledge of results, KR) frequency and its effects on learning by using a no-KR 24-hr retention test. Participants tossed a ball as close to the centre of the target as possible (10 points for the centre, followed by 9, 8, 7, 6...1 for each zone outside the centre). KR was provided immediately or delayed depending on the group participants were randomized to. Following the end of acquisition, a 24-hr no-KR retention test was conducted. Results from the study show improvements across acquisition for all groups with participants in the immediate KR group ( $M = 5.86$ ) demonstrating higher mean accuracy scores than those receiving delayed KR ( $M = 4.89$ ). However the performance effect of the immediate KR during acquisition was diminished when KR was removed during the retention test. The immediate KR during acquisition diverted participants' attention away from important intrinsic sources of feedback thus when removed during the no-KR retention test, the transient performance gains (indexed by toss accuracy) were eliminated. However following the delayed retention test, the delayed KR group outperformed the immediate KR group thus exemplifying the performance-learning paradox. Therefore, conducting delayed retention tests is imperative to infer learning as results from the end of acquisition may not be a strong indicator of persistent behavior.

## 1.2 Intrinsic Feedback

Sensory feedback signals (e.g., proprioceptive, visual, auditory) naturally produced during the movement are termed *intrinsic feedback* (Anderson, Magill, Sekiya, & Ryan, 2005; Kohl & Shea, 1995; van Vliet & Wulf, 2006). During motor skill

acquisition, the interpretation of the movement related intrinsic feedback is a key factor in learning (Anderson, Magill, & Sekiya, 2001; Sherwood, 2010; Wulf & Shea, 2004). Often times, the intrinsic feedback is compared to augmented feedback (e.g., information of learners' movement outcome success) to minimize movement errors. The interpretation of intrinsic feedback can be further explained by Schmidt's (1975) *recognition schema*.

The recognition schema allows the learner to compare their expected movement-related sensory information (i.e., what the movement should feel like; expected proprioceptive, visual, auditory, etc feedback) with their actual movement-related sensory experience (Schmidt, 1975). Similar to Adams' perceptual trace theory (1971), the recognition schema is formed by past experiences and augmented feedback. *Error-labeling* is defined as the learner's ability to discriminate between the expected and actual sensory consequences, based on the provision of augmented feedback regarding motor performance (i.e., knowledge of results, KR; Schmidt, 1975). The variation between the expected and actual sensory consequence indicates movement error. This is often indexed by absolute difference (AD) between the actual and estimated scores (Newell, 1974). AD should decrease as learners develop their error detection capabilities (Andrieux & Proteau, 2014; Guadagnoli & Kohl, 2001; Hogan & Yanowitz, 1978; Newell & Chen, 1974; Schmidt, 1975; Sherwood, 2010).

### **1.3 Knowledge of Results**

Outcome success about motor performance is often defined as knowledge of results (KR; Newell, 1974; Salmoni et al., 1984; Schmidt & Wrisberg, 2004). KR informs the learner with post-response information regarding the outcome of a motor task in

relation to the task goal (Adams, 1971; Schmidt & Lee, 2013). More importantly, the information from KR can help the learner understand their intrinsic feedback following a movement by forming a reference for correctness (Schmidt, 1975). KR can confirm, restructure, and/or fine tune movements to meet the motor task goal on subsequent attempts (Salmoni et al., 1984). In key-pressing timing tasks (e.g., Chiviaowsky & Wulf, 2002; Patterson et al., 2014), KR provides meaning of movement-outcome feedback since quantifying time can only be arbitrarily deduced (i.e., learners may not know what five button pushes in 2000 ms feels like). This allows the learner to make sense of movement-related intrinsic feedback, therefore performance errors can be adjusted for subsequent trials (Schmidt, 1975). For example, if the learner is to complete five button pushes in a total goal time of 2500 ms and their KR indicates their overall MT is 3000 ms, they know to speed up for upcoming trials.

A key factor in determining the success of learning is the scheduling of KR (e.g., immediate/delayed, summary, bandwidth, faded etc; for review, see Wulf & Shea, 2004). If scheduled inappropriately, KR may be used as a crutch, therefore preventing the active interpretation of important sources of intrinsic feedback (Salmoni et al., 1984). The importance for the learner to interpret their intrinsic feedback has been seen in a multitude of studies which test the *guidance hypothesis* (e.g., Salmoni et al., 1984; Schmidt, Young, Swinnen, & Shapiro, 1989). The guidance hypothesis was proposed to explain the dichotomy between KR frequency and learning. It was proposed KR can be used to correct movement errors on subsequent attempts, though frequent provision of KR decreases the ability to interpret intrinsic feedback during practice, therefore deterring motor skill learning (Salmoni et al., 1984). For example, Guadagnoli and Kohl

(2001) investigated the relationship between KR frequency and error estimation.

Participants were randomized to a 20% KR or 100% KR condition and were asked to strike a pad to produce a predetermined target force. Following each trial, KR was provided according to the KR frequency condition. Those in the 20% KR group received feedback of their force produced after every fifth trial. Those in the 100% KR group received feedback after every trial. Results from the no-KR retention test showed larger root mean square error (RMSE) and variable error (VE) for the 100% KR group suggesting high KR frequency deters learning, providing support for the guidance hypothesis. Learners seemingly relied on KR to support their motor performance. A method to mitigate reliance on KR during motor skill acquisition is to manipulate when KR is provided during practice (Wulf & Shea, 2004).

Reducing the amount or delaying the provision of KR encourages learners to process task-related intrinsic feedback on the no-KR trials (e.g., Anderson et al., 2005; Blandin, Toussaint, & Shea, 2008; Butki & Hoffman, 2003; Guadagnoli & Kohl, 2001; Park, Shea & Wright, 2000; Salmoni et al., 1984; Schmidt et al., 1989; Winstein & Schmidt, 1990). For example, Bruechert, Lai, and Shea (2003) investigated KR frequency and its effects on error detection during a force-production task. Participants were required to grip a dynamometer to produce three target forces (30%, 50%, and 70% of max force). Two groups were used based on KR frequency (50% or 100%). The 50% KR group received feedback on trials 1-3, but not on trials 4-6. The 100% KR group received feedback following each trial. KR was provided 2 seconds following the trial and verbal feedback of the actual force in pounds produced was given. The delayed retention test (24 hr, no-KR) required participants to estimate their own force produced (in lbs). Results

from acquisition showed the 100% KR group produced more errors (total force-production error in Newton units) than the 50% KR group. However during the no-KR retention test, total estimation error was smaller for those in the 50% KR group ( $M = 23.53$  lbs) compared to the 100% KR group ( $M = 35.67$  lbs). Additionally, retention test results showed lower VE scores for the 50% KR group. Error estimation during the delayed no-KR retention test was conducted to determine if the intrinsic error detection capabilities are enhanced by similar conditions, such as reduced KR frequencies.

Correlations between the estimated error and actual error indicated those in the 50% KR group developed stronger error detection capabilities ( $M = 0.69$ ) than the 100% KR group ( $M = 0.41$ ). A moderate effect size of 0.58 was also reported. Overall these results suggest reduced KR is conducive to developing an internal mechanism for error detection.

#### **1.4 Error Detection and Correction**

Learners subjectively estimating movement errors based on their intrinsic feedback in the absence of frequent feedback (e.g., 100% KR) facilitates motor skill acquisition (Sherwood, 1996). A method that has encouraged learners to interpret their intrinsic feedback when using a 100% KR acquisition frequency schedule is asking participants to estimate their motor performance (e.g., overall movement time or movement error) prior to receiving KR. Learners who estimate their performance compared to those who do not demonstrate superior motor performance, as well as error estimation on retention tests (e.g., Guadagnoli & Kohl, 2001; Green & Sherwood, 2000; Patterson et al., 2014; Swinnen, Nicholson, & Shapiro, 1990). Guadagnoli and Kohl (2001) referred to this subjective-estimation as *hypothesis testing*. After completing a

trial, the learner is asked to explicitly estimate the perceived outcome of their motor action relative to the task goal (e.g., force produced; Guadagnoli & Kohl, 2001, distance moved; Hogan & Yanowitz, 1978; Schmidt & White, 1972, toss accuracy; Liu & Wrisberg, 1997, movement time; Black, Wright, Magnuson, & Brueckner, 2005; Patterson et al., 2014) based on the active interpretation of their sensory feedback prior to receiving KR. An important role of providing KR to the learner following error estimation is to strengthen their error detection capabilities during motor skill acquisition (Adams, Goetz, & Marshall, 1972; Schmidt & White, 1972; Swinnen et al., 1990). KR manipulations (i.e., scheduling) during practice encourages learners to rely on their intrinsic feedback. KR provides meaning of the intrinsic feedback experienced by learners following the movement. A study by Guadagnoli and Kohl (2001) had participants strike a padded force transducer to reproduce a predetermined target force. Four experimental groups were used: a) 100% KR + error estimation, b) 100% KR + no estimation, c) 20% KR + 100% estimation, and d) 20% KR + no estimation. Those in the 100% KR received KR following every acquisition trial where the 20% KR group received KR after every fifth trial. Those in the estimation group verbally estimated the force-production error immediately following each trial. KR consisted of direction and magnitude of force production error. Approximately 24 hours following acquisition, 15 no-KR trials were conducted. No error estimation was required during this period for any participants. The 100% KR group produced lower RMSE ( $M = 241$  arbitrary units [au]) compared to the 20% KR group ( $M = 289$  au) thus estimating errors during acquisition coupled with a high KR frequency can enhance error detection capabilities. However, unlike previous studies such as Adams et al., (1972), Blandin & Proteau (2000) and

Sherwood (1996), the authors did not specifically assess the accuracy of the error estimation capabilities in terms of AD and/ or correlations.

Recently, Sherwood (2010) investigated the effects of error detection and correction during long and short arm movements. Participants were to move their arm to a target distance (reversal point) in a target goal time of either: a) 30°/210ms, b) 30°/350ms, c) 50°/210ms, or d) 50°/350ms. Five seconds following the movement, participants in all groups were required to estimate their reversal point (to the nearest degree) as well as their MT (in ms) for the just completed trial. Similar to Schmidt and White's (1972) study, Sherwood also referred to participant estimations of reversal point and MT as *subjective scores*. Following each estimate, KR of the actual reversal point and MT was provided (referred to as *objective scores*). To assess the participants' ability to correct error, correlations of the actual correction made with the required correction were conducted. Sherwood provided the example of, "... if the goal distance is 30° and the participant moves 25° on a trial, the required correction based on KR is + 5°" (pg. 302). Therefore, the value is correlated with the actual correction made on the following trial. Additionally, participant subjective scores on each trial were correlated with the objective scores. When considering reversal point (spatial error), results from subjective CEs were similar to objective CE results at the end of acquisition (30° group,  $M = 2.8^\circ$ ; 50° group  $M = 1.2^\circ$ ). During acquisition, the subjective scores for both groups were more consistent than the no-KR blocks based on VE. When considering MT (temporal error), subjective CEs were generally only 5-10 ms less than objective CEs. The mean objective-subjective differences in MT decreased from 50 ms  $\pm$  29 ms on the first block of acquisition to 25 ms  $\pm$  12 ms on the last block of acquisition. Additionally, MT objective-

subjective correlations increased from .20 in the first acquisition block, to .40 on the last acquisition block. The increase in correlation and reduction in the objective-subjective correlation with practice suggested that a temporal recognition schema was strengthened with practice (Schmidt, 1975; Sherwood, 2010).

More recently, Patterson, McRae and Lai (2014) conducted a temporal key-pressing study investigating the effects of invested cognitive effort during performance appraisal. Participants practiced a 5-digit key-pressing sequence in a goal MT of 2550 ms. Three experimental groups used were: a) performance estimation (P-E), b) performance recognition (P-R), and c) control (C). Following the completion of the key-pressing sequence, participants in the P-E group were asked to estimate their perceived MT (in ms). Those in the P-R group were asked to choose one of three MTs presented (one MT was their actual MT while the other two were either 20% greater than or less than their actual MT). Those in the C condition were not explicitly asked to engage in the estimation process. Following estimation (or not for C condition), KR was provided on all acquisition trials. The KR presented was the goal time, their estimated MT (only for P-E and P-R), actual MT, and timing error (difference between goal MT and actual MT). A delayed no-KR retention test (approximately 24 hours following the end of acquisition) was conducted. All participants completed 15 trials in the estimation condition, and 15 trials in the recognition condition. Results indexed by  $|CE|$  showed the groups required to estimate demonstrated superior learning in the no-KR delayed retention test (P-E,  $M = 240.5$ ; P-R,  $M = 217.5$ ; C,  $M = 365.7$ ). Additionally, performance appraisal accuracy indexed by AD and proportion correct (from recognition) was higher in P-E and P-R than C. These results lend further support to the benefits of performance estimation to enhance

error detection abilities as learners relied solely on their intrinsic feedback to hypothesize the success of their motor action during no-KR retention tests.

### **1.5 Augmented Sensory Information**

In our everyday lives, we may have generous amounts of task-related properties regarding performance embedded in the task-intrinsic outcome (i.e., vision of hand moving towards the target, vision of the target being hit etc...). The motor system generates an *efference-copy* from movement-related consequences (Schmidt, 1975). The efference-copy can be compared between the actual movement and desired movement enabling movement adaptation. The information from the efference-copy can be “fed forward” to generate the predicted sensory feedback that also predicts the expected sensory consequence (Adams, 1971; Schmidt, 1975). Therefore, this *feed-forward* system allows learners to anticipate what the movement outcome should feel like (Adams, 1971; Schmidt, 1975). In many key-pressing timing tasks (e.g., Black, et al., 2005; Chiviakowsky & Wulf, 2002; Lai, Shea, & Little, 2000; Patterson et al., 2014), hard key devices such as computer keyboards and serial-response boxes (SR-box) have been used. The hard key devices consist of physical keys that must be depressed to complete the intended action. The depression of the key provides learners with visual (e.g., seeing the depression of the key), auditory (e.g., hearing the click), and tactile feedback (e.g., the feeling of key displacement). Augmentation of sensory information is not required because the learner expects to receive auditory, visual and tactile feedback after the button has been pushed. The learner can attend to multiple sources of sensory information inherent in the motor task to compare movement-related intrinsic information with movement outcome.

*Soft key* devices such as touch screen devices (TSD) allow for custom virtual buttons to be programmed to perform different functions (Lee & Zhai, 2009). For example, the keypad for the pass-code lock screen on a mobile device appears different from the numeric keypad used to dial a telephone number. Both require numeric entry on a keypad to execute the given function, but the shape and location can be dynamically changed to suit user needs. As a result, the demand for TSD in public and private locations has increased due to the flexibility of design (Bachl, Tomitsch, Wimmer, & Grechenig, 2010). Additionally, the interface serves as both display and control due to the absence of moving parts (e.g., hard keys) allowing responses to be made directly on the display (i.e., control-on-display Lim, Ryu, & Kim, 2014). However, the intuitive *control-on-display* design poses a challenge for users (Lim et al., 2014). TSD lack much of the natural sensory information hard key devices afford. As a result, users must be more attentive to auditory and visual feedback. Therefore to address this issue, augmentation of sensory information is typically programmed into TSD in order to enhance the sensory experience (e.g., Akamatsu, Mackenzie, & Hasbrough, 1995; Bachl et al., 2010; Chen, Savage, Chourasia, Wiegmann, & Sesto, 2013).

Augmented sensory information allows the device to mimic the sensory information conventional hard key devices provide. These soft key interfaces can be programmed to vibrate (e.g., tactile sensory feedback; Altinsoy & Merchel, experiment 1, 2009), change colours (e.g., visual sensory feedback; Sears, 1991), and make a noise such as a 'click' (e.g., auditory sensory feedback; Altinsoy & Merchel, experiment 2, 2009; Hwangbo, Yoon, Jin, Han, & Ji, 2013) when touched. The effectiveness of augmented sensory information on TSD is often indexed by accuracy (e.g., total number of errors

made per trial, Hwangbo et al., 2013; Lim et al., 2014) and time to completion (e.g., words per minute, Park, Heo, & Lee, 2015; total time in seconds, Altinsoy & Merchel, 2009).

One distinct disadvantage of TSD is the absence of button displacement when depressed. Without this kinesthetic *feel* of pressing the button, users can only rely on auditory and visual feedback. Augmented tactile feedback supplements auditory and visual feedback when environmental conditions render them useless (e.g., in a loud and crowded environment). Simulation of tactile feedback includes vibration, piezoelectric actuation, pin matrices or ciliated surfaces (Harrison & Hudson, 2009). Hoggan, Brewster and Johnston (2008) designed an experiment to investigate the effects of incorporating tactile feedback into mobile touch screen buttons. They compared a regular physical keyboard, a standard touch screen and a touch screen with tactile feedback added on a mobile phone using actuators (created a vibration). Additionally, Hoggan et al., (2008) compared these three keyboards in a lab setting, and on a moving subway train to simulate real-life situations. Participants were shown a phrase and asked to type it into each keyboard as quickly and accurately as possible. Each participant used all three keyboards (order was counterbalanced) for the experiment. Over the span of three days, 30 of 500 random phrases were selected for each keyboard in each setting. When strictly comparing results from the standard touch screen and tactile touch screen keyboards, the tactile keyboard resulted in higher average percent of phrases entered correctly in the lab and on the subway ( $M = 82.7\%$ ,  $80\%$ ;  $M = 69.6\%$ ,  $65.8\%$  respectively). Furthermore, the average time to enter each phrase (in seconds) was faster for the tactile keyboard in the lab and on the subway compared to the standard touch screen keyboard ( $M = 20s$ ,  $22s$ ;  $M$

= 25s, 27s, respectively). Despite obvious benefits of augmented tactile feedback in consumer electronics (e.g., mobile phones), many of the devices today are not programmed to simulate tactile feedback on touch due to high costs and scalability (i.e., most devices are programmed for “whole-body” vibration, rather than the specific spot touched).

Similar to tactile feedback, there has been much research in auditory feedback with results suggesting improvements in performance over purely visual displays (Chang & O’Sullivan, 2005). Hoggan et al. (2009) investigated text entry performance on a mobile phone touch screen with visual, auditory, or tactile feedback. A between-subjects design was used with conditions of touch screen keyboard with audio, tactile, and visual feedback. Similar to the earlier 2008 study conducted by Hoggan et al., participants were shown a phrase and asked to enter it as quickly and accurately as possible using the on-screen keyboard. A random set of 60 phrases was selected to be completed for all conditions. The tactile feedback was based on the design by Hoggan et al. (2008) and the auditory feedback was a standard wave tone (i.e., beep). Unfortunately, authors did not report how visual feedback was presented to participants. Results from the study showed the highest average percentage of correct phrases and text entry rate (words per minute) were seen in the tactile feedback, followed by auditory and lastly visual feedback. To add further support to the benefits of augmented auditory feedback, Lee and Zhai (experiment 1, 2009) investigated the effect of various feedback conditions (auditory, vibro-tactile, both and none) on touch screen keyboard performance. The task used was a multiplication operation using number (0-9) and operator ( $\times$  and  $=$ ) buttons on calculators. Each trial of the 15 trials, participants were required to enter 8 digits and 2

operators. The example authors provided was  $1450 \times 9276 =$ . The auditory feedback was a 130 ms long system beep sound, and the vibro-tactile feedback was 50 ms long vibration that was implemented through an actuator on the mobile device. When strictly comparing results from auditory and no-feedback, numeric input speed and accuracy were higher in auditory conditions. Although mean values were not reported, the results from the study support the notion that providing users with auditory feedback is more beneficial than not.

Without enhancement of tactile feedback on TSD, users can only rely on auditory and visual information. Like tactile feedback, visual information can be added to provide synthetic feedback to the user to compensate for the lack of intrinsic tactile feedback in soft keys. Oftentimes, visual information results in a change of button size (e.g., the button quickly expands when touched then returns to its original size when released) or button colour (e.g., a white button may quickly change to black then back to white). However, much of the TSD literature exploring various methods to enhance TSD performance neglects the effect of augmented visual information alone. Akamatsu et al., (1995) compared tactile, auditory and visual feedback in a pointing task using a mouse. Although using a mouse is a different form of manual aiming compared to touch screen use, authors noted the visual system provides the most informative sensory feedback. However, visual information is not apparent until the action is initiated and executed. If this concept is applied to TSD, researchers may assume the user received enough visual information by watching their finger moving towards the target. This may be an indicator of why many studies investigating augmented sensory feedback focus specifically on tactile, auditory, and audio-tactile feedback.

## 1.6 Specificity of Practice

Practice provides the learner with the ability to determine the source(s) of afferent information that is likely to ensure optimal movement accuracy (Coull, Tremblay, & Elliot, 2001). The theory of *specificity of practice* states the amount of transfer from practice conditions to retention is optimized if retention conditions are similar to those of practice (Proteau, 1992). It is often noted in motor learning literature that the visual feedback received following a response is the dominant source of information. When vision is withdrawn (e.g., in retention tests), a detrimental impact on motor performance is observed for participants that practiced under conditions where visual information was available. In contrast, participants who practice without vision and transfer to a vision transfer test show smaller detriments in learning (Coull, et al., experiment 1, 2001; Blandin, et al., experiment 1, 2008). In a study conducted by Coull, Tremblay and Elliot (2001), the specificity of practice hypothesis was examined using a tracking task in visual and auditory conditions. Participants were to maintain the grip force on a dynamometer at a target line in 10 or 100 acquisition trials (4 experimental conditions; number of trials  $\times$  feedback type). Those with visual feedback were asked to match and maintain their force production (denoted as a blue line on a computer monitor) to the target gray line that spanned the horizontal display for 15 seconds. Those in the auditory feedback condition received auditory tones through a headset and were asked to match the two. Two delayed (24 hours) no-KR retention tests consisting of 10 trials were completed (5 trials of the same afferent condition as acquisition and 5 trials performed under the other sensory modality). Analysis of no-KR retention test data showed a significant decrease in performance when afferent information was changed as indexed by RMSE in both 10 and

100 trial groups. The RMSE was higher when those who practiced under visual conditions switched from the visual transfer test to the auditory test ( $M = 4.0$ ,  $M = 3.1$ ; 10 trials, 100 trials). In contrast, the RMSE scores were not as large for those in the auditory condition when performing the visual transfer test ( $M = 1.6$ ,  $M = 1.4$ ; 10 trials, 100 trials). These results lend further support that removing visual feedback following practicing the task with visual feedback leads to detriments in learning. Specifically, the impact of learning on those who practice under auditory conditions was less detrimental when performing the task under the same and different conditions compared to the group who practiced with vision during acquisition.

A series of studies have investigated the role of visual information in performing motor tasks as a function of the type of practice (Blandin et al., 2008; Proteau, 1992; Robin, Toussaint, Blandin, & Vinter, 2004). The specificity of practice hypothesis has been supported with manual aiming (Proteau, Marteniuk, & Levesque, 1992), video-aiming (Robin et al., 2005), flexion-extension movements (Blandin et al., 2008), powerlifting (Tremblay & Proteau, 1998), and key-pressing (Wright & Shea, 1991). For example, Blandin et al. (2008) investigated the detrimental effect of withdrawal of vision on a delayed transfer test following practice of an arm extension-flexion movement. Participants were asked to make a sequence of extension-flexion arm movements (on a lever) to produce the spatial (forearm angle of  $\sim 85^\circ$ ) and temporal (1500 ms) aspects of the goal presented to them each trial. The movement pattern was produced during acquisition in proprioception + vision (PV) or proprioception (P) in either 100% KR or 33% KR conditions. In the PV condition, participants were shown a cursor displayed on a monitor indicating the actual position of the arm lever. In the P condition, the cursor

indicating limb position was not shown to participants. Following each trial, KR indicating the goal and actual movement position was displayed. Approximately 24 hr following acquisition, 18 transfer trials without vision of the lever position and KR were performed. Results of the study based on RMSE (deviation of actual pattern from the goal pattern) during acquisition indicated those in the PV condition produced lower error scores than those in the P condition regardless of the amount of KR received. However results from the no vision, no-KR transfer test indicated both the P-33% KR and the P-100% KR groups outperformed the PV-33% KR and PV-100% KR groups. The results from acquisition with vision (PV groups) to transfer without vision support the traditional specificity of practice hypothesis. Vision was an important source of information used to improve acquisition in performance but removing visual information was more detrimental to the PV group than the P group. It was suggested the removal of a dominant source of information (i.e., vision) was detrimental to performance further lending support to the specificity of practice hypothesis. Furthermore, results suggest the central nervous system (CNS) chooses the most efficient sensory information in order to efficiently complete a motor task.

In summary, the examination of KR frequency on motor skill acquisition is a widely researched area in motor learning. Frequent and immediate KR deters learning (for review see Salmoni et al., 1984) but this effect can be circumvented when learners are required to estimate their performance outcome prior to receiving KR (e.g., Guadagnoli & Kohl, 2001). Because the learner must actively interpret sources of intrinsic feedback from the motor movement, reliance on KR is mitigated. However, recent advances in technology have created a problem for those using TSD. These TSD lack the sensory information inherent in hard key interfaces thus creating a challenge for learners to interpret intrinsic feedback. Although it is evident sensory information must be augmented to TSD (e.g., Altinsoy & Merchel, 2009; Hwangbo, et al., 2013), it remains unclear which sensory modality best facilitates error detection in the user.

## CHAPTER 2: RATIONALE

### 2.1 Introduction

The usefulness of feedback in the learning of motor skills has been undeniable (for review, see Salmoni et al., 1984). Sensory feedback signals (e.g., proprioceptive, visual, auditory) naturally produced following a movement are defined as *intrinsic feedback* (Kohl & Shea, 1995). Intrinsic feedback serves as vital information for the learner in determining the success of a movement outcome (Anderson et al., 2005; Elliot, Chua, Pollock, & Lyons, 1995; Sigrist, Rauter, Riener, & Wolf; 2011; Wulf & Shea, 2004). The intrinsic feedback experienced by learners must be interpreted and compared to augmented external sources of feedback in order for error detection capabilities to be developed. Augmented feedback can help fine-tune movement accuracy by providing learners with information about the movement outcome success (Schmidt & Lee, 2013), often termed *knowledge of results* (KR) (Newell, 1974; Salmoni et al., 1984). KR informs the learner with post-response (i.e., terminal) information regarding their outcome of a motor task in reference to the movement goal (Adams, 1971). Providing participants with their actual movement time and the goal movement time allows them to adjust their motor performance on upcoming trials (Adams, 1971).

When KR is provided too frequently, it can have a negative effect on learning as frequent KR may prevent the learners' active interpretation of their movement related sensory feedback following a movement (Anderson et al., 2005; Chiviakowsky & Wulf, 2002; Ranganathan & Newell, 2009; Salmoni et al., 1984). Delaying the provision of KR following a motor response (i.e., 8 seconds; Swinnen, Schmidt, Nicholson, & Shapiro, 1990) can develop the learner's error detection capabilities based on their interpretation of intrinsic sensory feedback (Swinnen et al., 1990). Furthermore, instructing learners to

estimate movement performance prior to receiving KR has been found to facilitate skill acquisition and error detection capabilities (Guadagnoli & Kohl, 2001; Liu & Wrisberg, 1997; Patterson, et al., 2014; Swinnen et al., 1990).

One important role of KR for the learner is to strengthen their error detection capabilities for the motor skill being acquired (Adams et al., 1972; Swinnen et al., 1990). Liu and Wrisberg (1997) studied the effect of subjective performance estimation prior to the receipt of KR during motor skill acquisition. Participants tossed a ball to a target placed on the floor aiming for the centre of the target. The four groups used were: immediate KR, delayed KR, immediate KR + subjective estimation, and delayed KR + subjective estimation. The subjective estimation groups were asked to provide a rating of force, release and angle, and trajectory of the toss prior to receiving KR (either immediate or delayed). Results from the study (error estimation and throwing accuracy) showed subjective estimation of movement outcome and/or movement form enhanced retention of the task during no-KR trials compared to the groups who were not required to estimate. These results suggest engaging in performance estimates allows for more highly developed error detection mechanisms and capabilities compared to those who do not engage in performance estimation. The estimation process engages learners in the interpretation of intrinsic feedback. Therefore reliance on KR to guide them in more accurate movements is minimized.

Frontal areas of the brain (e.g., anterior cingulate cortex, prefrontal cortex, and connections to basal ganglia) are suggested to compose the executive system for cognitive control (Holroyd, Yeung, Coles, & Cohen, 2005). Increased neural activity in the ACC (anterior cingulate cortex) and frontal-central region of the brain has been seen

when KR indicating error is presented to learners (Nieuwenhuis, Holroyd, Mol, & Coles, 2004). More specifically, several studies have determined the ACC registers errors when they are detected by the learner with the provision of KR (e.g., Holroyd et al., 2005; Ullsperger, Nittono, & von Cramon, 2007). The recent evidence in neuroscience literature provides further evidence for an error detection mechanism in the learner previously supported by Schmidt's (1975) recognition schema.

The recognition schema allows the learner to compare their expected movement-related sensory information with their actual movement-related sensory experience (Schmidt, 1975). Any discrepancies between the actual and expected movement-related sensory consequence indicates movement error (Newell, 1974; Schmidt, 1975; Schmidt & White, 1972). Similar to the idea of a recognition schema, Kantak and Winstein (2012) more recently suggested a *motor memory* was updated based on the sensory consequence experienced. Learners are able to strengthen their reference of correctness from KR using movement-related sensory information during motor movements (Schmidt, 1975; Schmidt & White, 1972; Swinnen et al., 1990). The KR can confirm, restructure, and/or fine tune movements to meet the motor task goal on subsequent attempts (Salmoni et al., 1984; Schmidt, 1975). *Error-labeling* is defined as the learner's ability to discriminate between expected and actual sensory consequences based on the provision of KR (Schmidt, 1975). Therefore during no-KR trials, active interpretation of intrinsic sensory feedback from the learner aids in the development of error detection and correction mechanisms (e.g., Black et al., 2005; Bruechert et al., 2003; Guadagnoli & Kohl, 2001; Sherwood, 2009).

A strategy to engage learners in active movement-related sensory information interpretation has previously been referred to as *hypothesis testing* (Guadagnoli & Kohl, 2001). After completing a trial, the learner is asked to explicitly estimate the perceived outcome of their motor action based on the active interpretation of their sensory feedback prior to receiving KR (e.g., Adams et al., 1972; Guadagnoli & Kohl, 2001; Liu & Wrisberg, 1997; Newell, 1974). The learner assesses the accuracy of their hypothesis when comparing their perceived to actual movement outcome (i.e., KR). The cognitive processes the learner engages in during hypothesis testing are believed to strengthen the recognition schema (Schmidt, 1975). Engaging the learner in hypothesis testing is believed to prevent reliance on KR (van Vliet & Wulf, 2006). The learner's accuracy in error detection has been assessed through correlations and absolute difference (AD) of performance. AD is defined as the difference between the performer's actual and estimated motor performance, where a decrease in AD may indicate the strength of the recognition schema (Andrieux & Proteau, 2014; Guadagnoli & Kohl, 2001; Hogan & Yanowitz, 1978; Newell & Chen, 1974; Sherwood, 2010; Schmidt & Wrisberg, 1973).

The learning advantages associated with hypothesis testing have been demonstrated in sequential timing tasks (Patterson et al., 2014), ballistic timing tasks (Hogan & Yanowitz, 1978), force production tasks (Guadagnoli & Kohl, 2001), as well as observational learning tasks (Black et al., 2005). While the results of these studies highlight the benefits of actively engaging the learner in the cognitive processes required for error estimation, these motor tasks could be considered to be rich in intrinsic feedback. For example, a study conducted by Patterson and colleagues (2014) required participants to learn a temporal-spatial key pressing sequence on a serial-response (SR)

box. Learners experienced sensory feedback from the hard keys (i.e., physical keys such as a keyboard) as they were able to feel (e.g., tactile feedback), hear (i.e., auditory feedback) and see (i.e., visual feedback) the key depression naturally. Evidence from the delayed (approximately 24 hours following practice) no-KR retention tests showed superior learning (indexed by absolute constant error ( $|CE|$ ) and lower AD for the participants required to estimate their performance prior to receiving KR. These results suggest augmentation of sensory feedback (e.g., visual, auditory and proprioceptive) on a hard key device is not required since the learner may attend to multiple sources of sensory information inherent in performance of the motor task to formulate their hypothesis.

In our natural world, there is a plethora of sensory information inherently available when interacting with physical objects in our environment. For example when using a keyboard, the hard keys provide a natural 'click' noise providing confirmation the key has been depressed. Advances in technology have created human-environment interactions for learners that have reduced the sensory consequence commonly associated with a goal directed motor action. For example, there has been a surge in popularity of touch screen devices (TSD) in public (e.g., airports, grocery stores, banks, kiosks) and private locations (e.g., hospitals, offices, factories; Bachl, et al., 2010). The absence of external moving parts (e.g., hard keys such as those on a keyboard) on the TSD allows the user to input a response directly onto the display, defined as a soft key interface (i.e., virtual buttons programmed to perform multiple different functions; Lee & Zhai, 2009). Though the intuitive design of the TSD maximizes user control and ease of use, the soft key interface lacks much of the sensory feedback hard key (i.e., physical buttons that

must be depressed to complete an action) interfaces provide. The sensory experience for the user on a TSD is commonly augmented (e.g., Altinsoy & Merchel, 2009; Chen et al., 2013). Soft keys can be programmed to augment sensory feedback thus mimicking the experience users would feel when interacting with hard key devices. A soft key may be programmed to vibrate (i.e., tactile feedback), click (i.e., auditory feedback), and change colour (i.e., visual feedback) when touched (Altinsoy & Merchel, 2009; Hwangbo et al., 2013; Lee & Zhai, 2009; Lim et al., 2014) thus augmentation of sensory information plays a vital role in maximizing usability.

Positive effects for augmenting visual (e.g., Hwangbo, et al., 2013), auditory (e.g., Altinsoy & Merchel, experiment 2, 2009), and tactile (e.g., Hoggan et al., 2008, 2009) feedback to TSD have been reported. A study conducted by Hwangbo and colleagues (experiment 2, 2013) developed a software program to investigate the effect of augmented feedback types on touch screen performance. The types of feedback investigated were auditory, tactile, audio-tactile and no feedback. Auditory feedback was presented as a beep (70dB) and tactile feedback was presented as a vibration (intensity level of 1-beat vibration for 300ms). The task required participants to point at randomly presented square targets on a smartphone device. The time to complete the task was quickest in the audio-tactile condition ( $M = 24.00s$ ), followed by auditory ( $M = 26.98s$ ), none ( $M = 30.97s$ ) and finally, tactile alone ( $M = 33.26s$ ). Additionally, most errors were made in the no feedback condition ( $M = 9.61$ ), followed by tactile ( $M = 11.58$ ), auditory ( $M = 17.52$ ), and finally, audio-tactile ( $M = 18.68$ ) condition. Much of the touch screen literature focuses on augmenting auditory and tactile information specifically. Using

conventional TSD requires users to rely heavily on visual feedback (e.g., colour change of button; Park et al., 2015).

Currently, it remains unclear how the recognition schema and subsequent error detection capabilities are developed when using unimodal (visual or auditory) or multimodal (visual-auditory) augmentation of sensory information on TSD. The *specificity of practice* hypothesis suggests learning is most effective when practice conditions resemble those encountered during performance of the task (Proteau et al., 1992). During early practice, learners identify the source of information that is most likely to ensure movement accuracy on subsequent movement attempts (Blandin et al., 2008). Many studies have determined learners believe the optimal source of sensory feedback to ensure movement accuracy is vision (Blandin et al., 2008; Robin, Toussaint, Blandin, & Proteau, 2005; Wright & Shea, 1991). These studies focused on errors produced during no-vision transfer tests following the use of visual feedback during acquisition. Earlier work leading up to the specificity of practice hypothesis conducted by Wright and Shea (experiment 1, 1991) required participants to learn three 4-key pressing sequences on the keyboard. Participants were asked to place their left hand on keys a, s, d and f, and their right hand on keys j, k, l, and. When the stimulus was presented on the computer monitor, they were to complete the sequence with the corresponding finger. The sequence was displayed 1 of 3 ways: 1) position was at the top of the monitor, colour of the keys was blue, tone produced was 2500 Hz, shape of keys was diamond, 2) position was in the middle of the monitor, colour of the keys was red, tone produced was 1000 Hz, shape of keys was square, and 3) position of keys was at the bottom of the monitor, colour of the keys was yellow, tone produced was 300 Hz, shape of keys was

circles. Participants were not informed the sequence was the same over 108 trials because the presented stimuli differed by shape, colour, location and tone, but all three stimuli were presented to each participant. Retention data showed when stimuli conditions remained the same from acquisition, fewer errors were made. These results indicate our central nervous system (CNS) chooses the most effective sensory information to efficiently complete a motor task, but this may be predicated on how the sensory information is prioritized in the recognition schema.

We have many day-to-day interactions with numeric keypads (e.g., ATM password, using a calculator, unlocking a pass code; Hwangbo et al., 2013) but traditional hard keys may not be adequate to satisfy the user preferences (e.g., size of device, button sizes cannot be changed, design itself may not look appealing; Irwin & Sesto, 2012). Soft key interfaces allow for greater flexibility when programming functions and design (i.e., adjustments of button size can be made, sensory feedback can be augmented; Irwin & Sesto, 2012). The challenge of using TSD is the lack of visual, auditory and tactile feedback it provides users with. More specifically, the disadvantage of TSD is it does not allow the user to feel key movement (i.e., depression when pushed) therefore an emphasis in research has been placed on augmented tactile feedback (e.g., Altinsoy & Merchel, 2009; Chang & O'sullivan, 2005; Hwangbo et al., experiment 2, 2013). Altinsoy and Merchel (2009) investigated the effects of tactile and audio-tactile feedback on touch screen performance. Participants were asked to input 16 numbers on a touch screen device as fast and as accurately as possible. Those in the audio only group received a tone as augmented feedback when the button was touched. Those in the audio-tactile group received the tone feedback as well as a vibration to the finger when the button was

touched. Lastly, those in the no feedback group received no auditory or tactile feedback. Results showed error rates (incorrect button touched) decreased when tactile and audio-tactile feedback was augmented compared to no feedback. Additionally, it was shown if both modalities were combined (auditory and tactile), errors were minimized (i.e., sensory redundancy). The augmentation of tactile sensory feedback helps the user interpret the sensory information from TSD with their experienced sensory consequence. Despite evidence suggesting performance gains when sensory feedback is augmented to TSD (i.e., auditory, tactile, and/or visual feedback; Akamatsu, et al., 1995; Altinsoy & Merchel, 2009; Hwangbo et al., 2013; Irwin & Sesto, 2012; Lee & Zhai, 2009; Lim et al., 2014), the role of augmented sensory information on developing error detection capabilities in the learner has not been examined.

## **2.2 Statement of the research problem**

Learning benefits when requiring participants to formulate estimates of their performance (i.e., hypothesis testing) prior to receiving KR have been seen (e.g., Guadagnoli & Kohl, 2001; Liu & Wrisberg, 1997; Patterson et al., 2014; Swinnen et al., 1990). Engaging the learner in hypothesis testing is believed to prevent reliance on KR as learners are required to interpret intrinsic feedback from the movement (van Vliet & Wulf, 2006). Specifically, engaging in hypothesis testing allows for more highly developed error detection mechanisms and capabilities compared to those who do not engage in performance estimation (Bruchert et al., 2003; Guadagnoli & Kohl, 2001; Patterson et al., 2014). However, development of error detection mechanisms may be contingent upon the amount of sensory information available for the learner to interpret.

A study conducted by Patterson et al., (2014) required participants to predict their overall movement time after entering a 5-key sequence on a SR box. Importantly, learners experienced augmented sensory feedback from the hard keys based on their obvious displacement and auditory click, thus augmentation of sensory feedback would not be required. The increasing popularity of TSD has created sensory information challenges for users (Bachl et al., 2010). The soft-key interface serves as both a display and control resulting in direct control over the action they want accomplished by simply touching the item directly on the screen (Irwin & Sesto, 2012). The TSD design inherently provides minimal amounts of tactile, visual, and auditory feedback for the user, thus sensory information must be augmented. Despite previous research demonstrating the benefits of augmenting visual, tactile and auditory information to minimize errors during numeric entry tasks (e.g., Akamatsu et al., 1995; Altinsoy & Merchel, 2009; Hoggan et al., 2008; Hwangbo, et al., 2013), it remains unclear how error detection capabilities are developed when using unimodal (visual or auditory) or multimodal (visual-auditory) augmentation of sensory information on TSD. Therefore the purpose of this thesis is to determine which source(s) of augmented sensory feedback aid in error detection processes when using a TSD.

## **CHAPTER 3:        METHODOLOGY**

### **3.1    Participants**

Forty-eight ( $N = 48$ , 24 men and 24 women) participants were recruited (i.e., class announcement) from Brock University's graduate and undergraduate student body with ages ranging from 19-27 years ( $M = 21.26$  years). All participants self-reported normal or corrected vision. Informed consent was acquired prior to beginning the experimental protocol and the study was cleared by the university's research ethics board (14-194).

### **3.2    Instrumentation**

A Dell 20 inch Touch Monitor (E2014T) was used for testing. It has a 43.20cm  $\times$  23.98cm (17.01"  $\times$  9.44") LED visual display with a resolution of 1600  $\times$  900 pixels. The monitor served as the display as well as the manual response input device. To input touch responses, participants were asked to touch a visually presented target on the monitor with the pad of their index finger from their non-dominant hand. The touch screen was rotated away from the participant 60° from the horizontal and adjusted so the top of the screen was below the participants' eye level. An adjustable chair was provided for the participants and participants were asked to position themselves so the monitor was within an arm's length (e.g., Jin, Plotcher, & Kiff, 2007).

E-Prime Professional version 2.0.8.74 (Psychology Software Tools, Inc., Sharpsburg, PA) was used to create a customized interface display on a Dell Windows 7 Professional 32-bit operating system. Timing, presentation of the visual stimulus, and collection of all motor performance indices was controlled by the E-Prime software.

The soft-key layout was configured in a telephonic layout containing nine square soft-keys in a 3 $\times$ 3 grid. Each key was 20mm  $\times$  20mm (measured from edge-to-edge) with

3mm spacing between keys (Colle & Hiszem, 2004) and keys were outlined in a 3mm blue border on a black background (see Appendix D, Appendix E). Each soft-key was labeled with a number ranging from 1-9 starting from the top left soft-key and continuing left to right in a zigzag pattern ending in the bottom right soft-key (number 1 starts in the top left soft-key and number 9 ends in the bottom right soft-key). The target numeric sequence was displayed above the keypad in white Courier New font until the trial was completed (Appendix D). An external Targus keypad was used for various self-report measures (e.g., performance estimation) with key sizes of 19.05 mm × 19.05 mm. Keys were to be depressed more than 3.81 mm to register a response.

### **3.3 Task**

Participants were asked to learn a novel 5-digit sequence (4-7-2-9-5) in a pre-determined goal time of 2550 ms. Participants were instructed to use their non-dominant hand to increase the novelty of the task.

### **3.4 Procedure**

Prior to the start of the acquisition period, each participant was asked to verbally provide age, gender, hand dominance, and vision status (normal or corrected normal). A pre-test was conducted on customized E-Prime software (Version 2.0.8.74 Psychology Software Tools, Inc., Sharpsburg, PA) to assess participants' reaction time to a stimulus when receiving auditory and visual cues separately. A series of 22 randomized trials presented a white visual fixation (5 mm × 5 mm '+' within a 25 mm × 25 mm soft-key) in the centre of the screen on a black background with a random variable foreperiod (1200, 1400, 1600, 1800, 2000 ms) before an audio or visual stimulus was delivered (Appendix I). The first two trials were not used in data analysis but were included in the

pre-test to allow participants to familiarize themselves with the protocol. The auditory stimulus was a 625Hz sine tone played at a bit rate of 1411 kbps (kilobytes per second) for 100 ms. The visual stimulus was a grey soft-key (25 mm × 25 mm) which replaced the visual fixation for 100 ms (Appendix J). Participants were asked to place their non-dominant index finger on a pre-defined starting position on the 'Dell' logo located on the bottom edge of the monitor, at the participants' midline. Participants were to touch a single soft-key located on the center of the screen (soft key size was 20 mm × 20 mm) upon hearing either the tone or seeing the gray soft-key appear. There were 10 audio and 10 visual stimulus trials presented for the pre-test in random order for a total of 20 trials. The results from the pre-test were not presented to the participant, nor did they determine participant group assignment.

Participants were randomized into 1 of 4 groups, balanced by gender: visual feedback (VF,  $n = 12$ ), auditory feedback (AF,  $n = 12$ ), visual-auditory feedback (VAF,  $n = 12$ ), and no feedback (NF,  $n = 12$ ). Prior to acquisition trials, all participants viewed a series of instruction screens outlining the experimental protocol. Participants were shown a picture indicating the optimal location on their fingertip to use when interacting with the touch screen. Participants had three opportunities to interact with soft-keys presented on the touch screen. The size of the touch screen replicated the size being utilized in the experiment. Participants viewed a series of soft-keys (20mm × 20mm) and were instructed to touch the centre of each key using the index finger of their non-dominant hand. This allowed participants to familiarize themselves with the motor demands required to successfully interact with the touch screen (e.g., amount of force required for a response to be registered by the touch screen). Next, all participants performed two pre-

acquisition trials to familiarize themselves with their respective experimental protocol. In the two pre-acquisition trials, participants were asked to enter a 5-digit sequence (9-1-2-4-7) in a goal time of 2550 ms. Following each pre-test trial, two performance estimation screens followed. First, participants were asked to enter their perceived time (in ms) to enter the 5-digit number sequence using the Targus external keypad (Appendix F). Next, participants were presented with a confidence scale asking, “*How confident are you that your estimated time matches your actual movement time?*” on a 5-point scale from 1 to 5. A key press of 1 represented “*No-confidence*”, button 3 represented “*Moderately-confident*” and button 5 represented “*Completely-confident*”. The self-report performance estimation occurred on all 100 acquisition trials. The 5-digit sequence (9-1-2-4-7) used in the pre-acquisition trials was not used in the experiment. Following the pre-acquisition trials, 100 acquisition trials were performed by the participant.

During acquisition, all participants were instructed to enter the 5-digit sequence (4-7-2-9-5) as close to the goal-time (2550 ms) as possible using the soft-keys on the touch screen monitor. This stimulus screen (Appendix D) remained visible until the participants completed five motor responses on the soft-key display. All participant responses, independent of the soft-key depressed, were recorded by E-prime. If the 5-digit sequence was entered incorrectly, participants were shown an *INCORRECT SEQUENCE* screen and participants reattempted the sequence on the next trial. If the correct sequence was entered, participants were asked to enter the total time they believed it took for them to enter the 5-number sequence (Appendix F), using the external keypad. Following the estimation, participants were presented with a confidence scale asking, “*How confident are you that your estimated time matches your actual movement time?*”

on a 5-point scale from 1 to 5. A key press of 1 represented “*No-confidence*”, button 3 represented “*Moderately-confident*” and button 5 represented “*Completely-confident*” (Appendix G). A feedback screen followed displaying: goal time (2550 ms), estimated time (in ms), actual movement time (in ms), and the difference between the goal time and movement time (in ms) indicating direction (see Appendix H). The duration of the feedback display was self-determined and was terminated when participants ‘PRESS ENTER TO CONTINUE’. Following the 100 trials of the acquisition period, participants were asked to complete a 1-item survey similar to the NASA-TLX (Hart & Staveland, 1988) measuring perceived cognitive workload (Appendix K). All acquisition, retention and transfer trials required the participant to self-report an assessment of their motor performance and their perceived confidence in the accuracy of this judgement. During retention and transfer tests, no KR was provided.

Participants randomized into the VF condition saw the soft-key colour change from black to gray for the duration of 100 ms when each soft-key was touched in the movement sequence, indicating a response was made. Regardless of whether or not the motor response was correct, the selected key changed colours. Participants were also required to wear industrial grade earmuffs to minimize the possibility of receiving auditory feedback from finger contact with the touch screen.

Participants randomized to the AF condition only heard an audible ‘click’ at 1411kbps for 100 ms when the soft-key was touched. Regardless of whether or not the motor response was correct (i.e., correct button in the sequence), the touched soft-key produced an audible ‘click’. This stimulus screen (Appendix D) remained visible until five motor responses were made.

Participants randomized to the VAF condition received the sensory information being provided to the VF (soft-key colour change) and AF conditions upon the completion of each motor action. Regardless of whether or not that response was correct, the completion of the motor action on the soft-key produced *both* visual and auditory feedback. The stimulus screen (Appendix D) remained visible until the participant completed five motor actions.

Participants randomized to the NF condition did not receive the sensory information provided to the VF and AF conditions upon completion of a motor action. The soft-key display stimulus (Appendix D) remained visible until five motor actions were completed. Participants in NF also wore industrial grade earmuffs for the duration of the acquisition period to minimize any external auditory information inherent in interacting with the touch screen display.

### **3.5 Retention and Delayed Sensory Information Tests**

A delayed retention test (approximately 24 hours) after completion of the final acquisition trial was performed by all participants. The retention test consisted of 10 no-KR trials of the practice context experienced during the acquisition period. Immediately following the retention test, participants were asked to complete the 1-item cognitive workload questionnaire used during acquisition (Appendix K). Three additional delayed sensory information tests followed the retention test, which consisted of 10 no-KR trials of the other 3 experimental not performed during acquisition conditions. For example, the NF group from acquisition performed 10-trials of no augmented sensory information (nSI) while the visual augmented sensory information (vSI), auditory augmented sensory information (aSI) and visual-auditory augmented sensory information (vaSI) were the

remaining tests. The order of the remaining delayed sensory information tests were organized from the least amount of sensory information to the greatest (Coull et al., 2001). Following each set of 10 no-KR trials, participants were asked to complete the cognitive workload questionnaire. For example, a participant in the NF group, for their retention test (nSI), performed 10 no-KR trials with no visual or auditory cues upon completion of each motor action, similar to their acquisition practice context. The subsequent tests consisted of 10 no-KR trials of the aSI, vSI, and vaSI experimental condition (see Appendix A). The sequence and timing goal practiced in the acquisition period remained as the task goal in these tests. Participants were also required to self-report their perceived movement time and confidence level after each retention trial, similar to the acquisition period, yet in the absence of KR. When completing the vSI and nSI, all participants were required to wear industrial grade earmuffs to minimize any auditory feedback from finger contact on the monitor. Following each set of 10 no-KR trial (e.g., vSI, aSI, vaSI), participants were asked to complete the cognitive workload questionnaire. There were a total of 40 trials during day-two of the experiment (4 blocks of 10 trials). Following completion of the fourth test, participants were asked to rate from best to worst which setting (colour change, click noise, colour change and click noise, and nothing) was most helpful in completing the sequence in the goal time of 2550 ms.

### **3.6 Dependent Measures**

To assess motor performance in acquisition and retention/ delayed tests, the dependent variables of interest were absolute constant error ( $|CE|$ ; absolute difference between goal time – actual performance time), variable error (VE), absolute difference score (AD; estimated movement time – actual movement time), and confidence ratings.

A single item based on the NASA-TLX was used to assess subjective cognitive workload when interacting with the touch screen. The ranking order of touch screen setting helpfulness was used to assess users' personal preference of which sensory modality users rather use when completing this timing task.

### **3.7 Data Analysis**

For pre-test data, a 4 (experimental condition; VF, AF, VAF, and NF)  $\times$  2 (test: auditory, visual) analysis of variance (ANOVA) with repeated measures on the test was conducted. Pre-test data were used to compare the reaction time of the auditory and visual scores. Each participant's mean scores were used to assess whether there were pre-existing tendencies for the individual to react more towards auditory or visual information.

For the acquisition phase of the experiment, mean VE and |CE| were grouped into 10 blocks of 10 trials. The VE and |CE| dependent variables were analyzed separately using a 4 (experimental condition: VF, AF, VAF, and NF)  $\times$  10 (blocks) ANOVA with repeated measures on blocks. To assess error estimation accuracy during the acquisition period for each condition, mean AD as well as confidence ratings were analyzed separately using a 4 (experimental condition: VF, AF, VAF, and NF)  $\times$  10 (blocks) ANOVA with repeated measures on block. Means from each subjective rating from a workload questionnaire based on the NASA-TLX were analyzed using a 4 (experimental condition: VF, AF, VAF, and NF)  $\times$  1 (1-item question: perceived cognitive workload) ANOVA.

For retention/delayed tests, mean VE, |CE|, AD, and confidence ratings were averaged into 4 blocks consisting of 10 trials each. They were analyzed separately in

four, 4 (experimental condition: VF, AF, VAF, and NF)  $\times$  1 (retention tests: vSI, aSI, vaSI, and nSI) ANOVAs. Means from each subjective ratings from a workload questionnaire based on the NASA-TLX were analyzed using a 4 (retention test: vSI, aSI, vaSI, and nSI)  $\times$  1 (1-item question: perceived cognitive workload) ANOVA with repeated measures on the last factor.

For all measures (i.e., |CE|, VE, AD, confidence, and perceived workload) analyses, SPSS IBM Version 20 was used. A significance level of  $p < 0.05$  was used for all analyses. Any values greater than two standard deviations from the mean were defined as statistical outliers and were removed from analysis (Fields, 2009). Estimated effect sizes were reported as partial eta squares ( $\eta_p^2$ ). Post-hoc comparisons were conducted using a Tukey's HSD. A Mauchly's test was conducted to determine if there was a violation of sphericity. Violations of sphericity were corrected using the Greenhouse-Geisser procedure.

### **3.8 Experimental Predictions**

Based on existing literature, the following experimental predications were made:

#### **3.8.1 Acquisition**

##### **Objective measures.**

- 1) The VF, AF, and VAF group would outperform the NF group as evidenced by lower |CE|, and VE scores (e.g., Akamatsu et al., 1995; Hwangbo et al., 2013; Lee & Zhai, 2009). It was predicted the conditions with augmented sensory information would outperform the NF condition because the sensory experience was being augmented regardless of the type of sensory information.

**Subjective measures.**

- 2) The VF, AF, and VAF groups would demonstrate lower AD scores than the NF group. Furthermore, the NF condition would report lower confidence scores than the VF, AF, and VAF condition based on the increased difficulty in assessing motor performance in the absence of augmented feedback (Patterson et al., 2014).
- 3) It was predicted a lower perceived cognitive workload score would be reported (based on the NASA-TLX) in the group with multiple sources of augmented information (i.e., VAF) compared to those with one or no sources of augmented sensory information (i.e., VF, AF, NF; e.g., Hoggan et al., 2009; Hwangbo et al., 2013).

**3.8.2 Retention****Objective/ subjective measures.**

- 4) During the **no augmented feedback** (nSI) test:

*Objective:* It was predicted the NF group would outperform the VF, AF, and VAF group as evidenced by lower |CE|, and VE scores. Removal of augmented sensory information for the VF, AF and VAF groups will result in detriments in performance as sensory information is being removed (e.g., Coull et al., 2001).

*Subjective:* It was predicted the NF group would demonstrate lower AD scores than the VF, AF, and VAF groups. Additionally, the NF group will report the highest confidence ratings and lowest perceived cognitive workload compared to the other experimental groups as this context replicated their acquisition condition.

- 5) During the **auditory augmented feedback** (aSI) sensory test:

*Objective:* It was predicted the auditory and NF groups would outperform the visual and visual-auditory group as evidenced by lower |CE|, and VE scores. However, there would be no statistically significant difference between AF and NF groups as the NF group would receive augmented sensory information not received during practice. Removal of visual information for the VF and VAF group would be detrimental to performance during the retention tests compared to AF group (Coull et al., 2001). It was predicted the VF and VAF groups would perform similarly.

*Subjective:* It was predicted the AF and NF groups would demonstrate lower AD scores compared to the VF and VAF group. Additionally, the AF and VAF groups would report the highest confidence ratings and lowest perceived cognitive workload compared to the VF and NF group.

- 6) During the **visual augmented feedback** (vSI) sensory test:

*Objective:* No group differences were expected. Vision is noted as the most dominant source of sensory information used therefore it was predicted all four groups will demonstrate similar performance as evidenced by |CE|, and VE (Blandin et al., 2008; Coull et al., 2001).

*Subjective:* It was predicted the VF, and VAF groups would report higher confidence ratings than the AF and NF group despite no group differences in AD. However, the cognitive workload ratings would be similar (i.e., low perceived workload) across all groups, as visual information is predominately used when available (Blandin et al., 2008).

- 7) During the **visual-auditory augmented information** (vaSI) sensory test:

*Objective:* It was predicted all four groups would demonstrate similar performance as evidenced by |CE|, and VE. Similar to prediction number 6, vision is noted as the most dominant source of afferent sensory information (Blandin et al., 2008) therefore the addition of augmented visual and/or visual-auditory information would benefit all groups.

*Subjective:* It was predicted all groups would demonstrate similar performance as evidenced by AD. Additionally, there would be no differences between groups when reporting confidence levels and cognitive workload. Specifically, it was predicted confidence ratings for all groups would be higher than in the aforementioned tests, as each group would receive the most augmented sensory information available. Furthermore, it was predicted reported mean cognitive workload scores would be lower for all experimental groups compared to the aforementioned tests (Hoggan et al., 2009; Hwangbo et al., 2013).

## CHAPTER 4: RESULTS

### 4.1 Pre-test

The group  $\times$  test interaction was not statistically significant,  $F(3, 44) = 2.47, p = .07$ . The results show that there was no significant effect of group on reaction time,  $F(3, 44) = .45, p = .72$  (table 1, figure 1). However, there was a main effect for test,  $F(3, 44) = 31.93, p < .001, \eta_p^2 = .42$ . The post-hoc analysis revealed participants performed the auditory reaction time test ( $M = 783.62, SD = 153.18$ ) faster than the visual reaction time test ( $M = 864.50, SD = 143.86$ ).

### 4.2 Acquisition

#### 4.2.1 Absolute constant error (*|CE|*)

Mauchly's test of sphericity indicated the assumption of sphericity was violated ( $\chi^2(44) = 207.56, p < .001$ ). To correct for the violation of the assumption, the Greenhouse-Geisser was performed. The group  $\times$  block interaction was not statistically significant,  $F(10.33, 151.51) = .64, p = .78$ . Additionally, there were no significant differences between groups,  $F(3, 44) = .72, p = .55$ . However, there was a main effect for block,  $F(3.44, 151.51) = 7.98, p < .001, \eta_p^2 = .15$ . The post-hoc analysis revealed block 1 ( $M = 397.92, SD = 219.80$ ) had higher *|CE|* compared to blocks 4 ( $M = 249.29, SD = 130.40$ ), 5 ( $M = 246.31, SD = 138.15$ ), 6 ( $M = 233.17, SD = 147.58$ ), 7 ( $M = 248.21, SD = 185.43$ ), and 10 ( $M = 247.86, SD = 153.57$ ). Additionally, block 2 ( $M = 321.55, SD = 170.44$ ) had higher *|CE|* compared to block 6 (table 2, figure 2).

#### 4.2.2 Variable Error (*VE*)

Mauchly's test of sphericity indicated the assumption of sphericity was violated ( $\chi^2(44) = 84.07, p < .001$ ). To correct for the violation of the assumption, the

Greenhouse-Geisser was performed. The group  $\times$  block interaction was not statistically significant,  $F(19.64, 288.01) = 1.14, p = .31$ . Additionally, there were no significant differences between group,  $F(3, 44) = 2.15, p = .11$ . However, results revealed a significant main effect for block,  $F(6.55, 288.01) = 7.16, p < .001, \eta_p^2 = .14$ . The post-hoc analysis revealed block 1 ( $M = 321.19, SD = 172.95$ ) had higher VE compared to blocks 4 ( $M = 198.01, SD = 107.26$ ), 6 ( $M = 156.81, SD = 72.60$ ), 7 ( $M = 170.00, SD = 110.68$ ), 9 ( $M = 187.60, SD = 118.26$ ), and 10 ( $M = 197.55, SD = 133.52$ ). Additionally, block 2 ( $M = 253.92, SD = 138.09$ ) had higher VE than blocks 6 ( $M = 156.81, SD = 72.60$ ) and 7 ( $M = 170.00, SD = 110.68$ ), as well as block 3 ( $M = 231.65, SD = 137.80$ ) and 6 (table 2, figure 3).

#### 4.2.3 *Absolute Difference (AD)*

Mauchly's test of sphericity indicated the assumption of sphericity was violated ( $\chi^2(44) = 74.19, p = .003$ ). To correct for the violation of sphericity, the Greenhouse-Geisser was performed. The group  $\times$  block interaction was not statistically significant,  $F(20.05, 294.04) = .71, p = .81$ . Additionally, there were no significant differences between group,  $F(3, 44) = 2.74, p = .54$ . However, the results revealed a significant main effect for block,  $F(6.68, 294.04) = 2.41, p < .05, \eta_p^2 = .052$ . The post-hoc analysis revealed block 1 ( $M = 335.88, SD = 153.22$ ) had highest AD compared to block 7 ( $M = 240.48, SD = 142.30$ ) and 10 ( $M = 134.36, SD = 134.36$ ; table 2, figure 4).

#### 4.2.4 *Confidence Ratings*

Mauchly's test of sphericity indicated the assumption of sphericity was violated ( $\chi^2(44) = 69.55, p = .009$ ). To correct for the violation of the assumption, the Greenhouse-Geisser was performed. The group  $\times$  block interaction was not statistically

significant,  $F(18.64, 27.41) = 1.51, p = .08$ . Additionally, there were no significant differences between group,  $F(3, 44) = 2.24, p = .097$ . However, results indicated a significant main effect for block,  $F(6.21, 273.41) = 2.92, p < .01, \eta_p^2 = .062$ . The post-hoc analysis revealed block 7 demonstrated the highest level of confidence ( $M = 3.55, SD = .70$ ) compared to block 1 ( $M = 3.26, SD = .49$ ), block 2 ( $M = 3.49, SD = .61$ ) and block 4 ( $M = 3.50, SD = .60$ ; figure 5).

#### **4.2.5 Subjective Workload Ratings**

The one-way ANOVA did not indicate significant differences between groups when rating subjective cognitive workload,  $F(3, 44) = 1.85, p = .15$ . However, the no feedback condition ( $M = 3.17, SD = .89$ ) rated their perceived cognitive workload higher compared to VF ( $M = 2.33, SD = .94$ ), AF ( $M = 2.83, SD = .67$ ), and VAF ( $M = 2.92, SD = 1.03$ ), respectively (figure 6).

### **4.3 Retention**

#### **4.3.1 No Augmented Feedback Test (nSI)**

##### *Absolute constant error (|CE|)*

The results for the ANOVA did not indicate a significant main effect for group,  $F(3, 44) = .11, p = .95$  (table 3, figure 7).

##### *Variable Error (VE)*

The results for the ANOVA indicated a significant main effect for group,  $F(3, 44) = 4.09, p < .05, \eta_p^2 = .22$ . The post-hoc analysis revealed AF ( $M = 151.77, SD = 83.24$ ) demonstrated the lowest VE compared to VAF ( $M = 157.24, SD = 112.27$ ), and NF ( $M = 294.87, SD = 176.92$ ; table 3, figure 8).

*Absolute Difference (AD)*

The results for the ANOVA did not indicate a significant main effect for group,  $F(3, 44) = .34, p = .79$  (table 3, figure 9).

*Confidence Ratings*

The results for the ANOVA did not indicate a significant main effect for group,  $F(3, 44) = .39, p = .76$  (figure 10).

**4.3.2 Auditory Augmented Feedback Test (aSI)***Absolute constant error (|CE|)*

The results for the ANOVA indicated a significant main effect for group,  $F(3, 44) = 3.03, p < .05, \eta_p^2 = .17$ . The post-hoc revealed a significant difference where NF ( $M = 398.11, SD = 160.50$ ) demonstrated greater |CE| compared to VAF ( $M = 236.12, SD = 113.30$ ; table 3, figure 7). No other group differences were statistically significant.

*Variable Error (VE)*

The results for the ANOVA indicated a significant main effect for group,  $F(3, 44) = 8.82, p < .001, \eta_p^2 = .38$ . The post-hoc analysis revealed the NF condition demonstrated greater VE ( $M = 356.65, SD = 175.97$ ) compared to the VF ( $M = 170.65, SD = 74.98, p < .01$ ), AF ( $M = 187.87, SD = 90.08, p < .01$ ), and VAF ( $M = 149.17, SD = 66.71, p < .001$ ; table 3, figure 8) conditions. All other group comparisons were not statistically significant.

*Absolute Difference (AD)*

The results for the ANOVA indicated a significant main effect for group,  $F(3, 44) = 83.47, p < .05, \eta_p^2 = .19$ . A follow-up post-hoc analysis indicated a significant

difference in AD between NF ( $M = 433.33$ ,  $SD = 180.09$ ) and VAF ( $M = 237.08$ ,  $SD = 126.92$ ; table 3, figure 9).

#### *Confidence Ratings*

The results for the ANOVA did not indicate a significant main effect for group,  $F(3, 44) = 1.06$ ,  $p = .38$  (figure 10).

#### **4.3.3 Visual Augmented Feedback Test (vSI)**

##### *Absolute constant error (|CE|)*

The results for the ANOVA did not indicate a significant main effect for group,  $F(3, 44) = .42$ ,  $p = .74$  (table 3, figure 7).

##### *Variable Error (VE)*

The results for the ANOVA indicated a significant main effect for group,  $F(3, 44) = 4.13$ ,  $p = .012$ ,  $\eta_p^2 = .22$ . The post-hoc analysis revealed VAF demonstrated lower VE ( $M = 143.58$ ,  $SD = 84.56$ ) compared to AF ( $M = 156.83$ ,  $SD = 82.01$ ) and NF ( $M = 312.97$ ,  $SD = 209.88$ ; table 3, figure 8). All other group comparisons were not statistically significant.

##### *Absolute Difference (AD)*

The results for the ANOVA did not indicate a significant main effect for group,  $F(3, 44) = .34$ ,  $p = .80$  (table 3, figure 9).

#### *Confidence Ratings*

The results for the ANOVA did not indicate a significant main effect for group,  $F(3, 44) = .34$ ,  $p = .78$  (figure 10).

#### 4.3.4 *Visual-Auditory Augmented Feedback Test (vaSI)*

##### *Absolute constant error (|CE|)*

The results for the ANOVA indicated a significant main effect for group,  $F(3, 44) = 4.91, p < .01, \eta_p^2 = .25$ . The post-hoc analysis revealed the AF ( $M = 237.69, SD = 104.74$ ) condition demonstrated lower |CE| compared to VAF ( $M = 262.23, SD = 93.40$ ) and NF ( $M = 365.60, SD = 177.74$ ; table 3, figure 7). No other group comparisons were statistically significant.

##### *Variable Error (VE)*

The results for the ANOVA indicated a significant main effect for group,  $F(3, 44) = 6.78, p < .01, \eta_p^2 = .32$ . The follow-up post-hoc analysis revealed AF ( $M = 117.31, SD = 46.91$ ) demonstrated lower VE compared to NF ( $M = 218.12, SD = 72.83$ ) and VAF ( $M = 157.53, SD = 49.57$ ; table 3, figure 8).

##### *Absolute Difference (AD)*

The results for the ANOVA indicated a significant main effect for group,  $F(3, 44) = 5.44, p < .01, \eta_p^2 = .27$ . The post-hoc analysis revealed the VAF condition ( $M = 270.59, SD = 136.31$ ) demonstrated lowest AD compared to AF ( $M = 271.00, SD = 189.41$ ) and NF ( $M = 566.63, SD = 292.21$ ; table 3, figure 9).

##### *Confidence Ratings*

The results for the ANOVA did not indicate a significant main effect for group,  $F(3, 44) = .70, p = .56$  (figure 10).

#### 4.3.5 *Subjective Workload*

The results for the RM-ANOVA indicated a significant main effect for test,  $F(2.59, 113.79) = 3.41, p < .05, \eta_p^2 = .072$ . The post-hoc analysis revealed subjective

workload was rated highest in the no augmented feedback test (i.e., nSI;  $M = 2.98$ ,  $SD = .93$ ) compared to the auditory augmented feedback test (i.e., aSI;  $M = 2.73$ ,  $SD = .89$ ) and the visual-auditory augmented feedback test (i.e., vaSI;  $M = 2.63$ ,  $SD = .87$ ; figure 11).

No other test comparisons were statistically significant.

## **CHAPTER 5: DISCUSSION**

The purpose of this study was to investigate the effects of augmented sensory feedback on subjective error detection accuracy during the acquisition of a soft key pressing sequence in a pre-determined goal movement time on a TSD. Human factors and ergonomics (HF/E) literature have shown positive performance advantages for augmenting TSD performance on numeric and alphabetic key entry tasks with visual (e.g., Hwangbo et al., 2013) and auditory (e.g., Altinsoy & Merchel, experiment 2, 2009) sensory feedback (e.g., Hoggan et al., 2008, 2009) based upon the decrease of erroneous key presses. To date, it was unknown if augmented sensory information would strengthen the subjective error detection process of the learner during motor skill acquisition on a TSD. Further, it was unknown what modality of augmented sensory feedback, alone or in combination, would best facilitate skill acquisition and the error detection processes of the learner during performance on a TSD. Therefore, to address this gap in knowledge, the purpose of the present experiment was to determine which augmented sensory modality would facilitate the error detection process of the learner during motor skill acquisition.

### **5.1 Performance-estimation and motor performance during acquisition**

During acquisition, it was predicted that participants in groups receiving augmented information that was either auditory, visual, or visual-auditory would outperform participants in the no-augmented sensory information group evidenced by lower |CE|, VE and AD scores during the acquisition period (e.g., Akamatsu et al., 1995; Hwangbo et al., 2013; Lee & Zhai, 2009). This prediction was not supported as the results indicated no group differences indexed by similar |CE|, VE and AD scores. However, performance of the

task (demonstrated by lower |CE|, and VE scores) as well as error-estimation (demonstrated by lower AD scores) both improved at similar rates over practice as indicated by block main effects for |CE|, VE and AD.

Past research focusing on subjective error detection in motor learning has used tasks expected to have an obvious sensory consequence that can easily be detected by the learner. For example, Guadagnoli and Kohl (2001) required participants to estimate the force produced by the impact on the hand from striking a pad in relation to the goal of the task. Sherwood (2010) required learners to displace their arm to a goal target distance (30° or 50°) and estimate their arm displacement in degrees from the starting position. In another example, Patterson and colleagues (2014) required learners to estimate their movement time following a serial-key pressing task in a goal movement time of 2550 ms. The physical keys on the SR box allow the learners to interpret their intrinsic feedback from the visual, auditory and kinesthetic systems from button depression. Overall, results from these studies demonstrated superior learning benefits (i.e., lower error scores, greater accuracy in movement estimation) of the motor task in the absence of KR (i.e., retention test) for learners who were required to make predictions of their movement outcome during the practice period compared to those who were not. Furthermore, learners were able to formulate predictions based on their sensory consequence (e.g., kinesthetic feedback) that was inherent to the motor task. However to our knowledge, the present study was the first to examine the contribution of various augmented information modalities for the development of error detection accuracy of the learner learning a soft-key pressing sequence on a TSD.

Comparable to previous research, results from the present study offer further insight into the benefits of performance-estimation during motor skill acquisition. When

learners were required to estimate their motor performance time during the practice period, the magnitude of error decreased (i.e., lower  $|CE|$ ), they became more consistent (i.e., VE) and made more accurate subjective predictions of movement time (i.e., AD) regardless of the presence or absence of augmented information, as indicated by block main effects. Requiring the learners to interpret the sensory consequence from the just-completed movement also increased confidence levels regarding their prediction of movement time. Subjective confidence ratings reflect the perceived confidence in the ability to accurately predict the success of the motor performance. It has been previously shown that the assessment of self-reported confidence in learners to accurately assess their performance is linked to the strength of performance-estimation capabilities (Newell, 1974). In the present experiment, participants were relatively accurate in predicting the accuracy of their motor performance, as indexed by AD measures, over the course of the practice period which may have led to higher subjective confidence ratings.

During acquisition, it was predicted that similar motor performance ( $|CE|$ , and VE) and subjective performance (AD) accuracy would be demonstrated by groups receiving augmented information compared to the no augmented sensory information group. The acquisition results did not support this prediction as no group differences were seen for  $|CE|$ , VE or AD during the acquisition period. It is possible all groups engaged in similar cognitive error detection and correction processes when required to estimate their perceived movement time prior to receiving KR. Several studies have shown the reliance on 100% KR schedules is circumvented and error detection capabilities strengthened when subjective estimation (i.e., performance-estimation) is performed prior to the receipt of KR on 100% of the acquisition trials (e.g., Guadagnoli & Kohl, 2001; Patterson

et al., 2014; Sherwood, 2009). However, providing KR immediately following the trial without requiring estimation allows learners to ignore interpretation of intrinsic feedback as they rely on KR to guide their future responses (Salmoni et al., 1984). The method of delaying KR receipt by subjective estimation alleviates the blocking of active error detection and correction processes. Learners are believed to interpret the movement-related sensory consequences of their just completed trial compared to if they were just provided KR following the motor action (Patterson et al., 2014). Therefore, all learners may have developed their motor memory to a similar strength such that the interpretation of intrinsic feedback experienced following the motor action influenced their subjective estimation. Thus, providing KR following subjective estimation allowed learners to understand the movement-related intrinsic feedback in relation to their prediction and outcome (Kantak & Winstein, 2012; Salmoni et al., 1984).

More recently, Kantak and Winstein (2012) proposed that error-detection is the result of a strengthened motor memory during the encoding phase of motor learning. The encoding phase is described as the development of a motor memory of the to-be-learned task allowing for the processing of task-related information (e.g., goal, outcome). The motor memory is strengthened through active interpretation of intrinsic feedback following a just-completed motor action. Thus, the results from the acquisition period suggest the error detection process developed in the encoding phase during motor skill acquisition was not differentially modulated by the different sources of augmented sensory feedback (as indicated by no |CE|, VE, or AD group differences). It is possible improvements in error-detection capabilities were the result of active interpretation of the task-related sensory feedback that was present for all groups during all motor trials.

To assess the strength of the error detection mechanism of participants as a function of augmented information provided during the acquisition period; KR was not provided during the retention period (Patterson et al., 2014; Russell & Newell, 2007; Sherwood, 2009). This allowed us to: 1) determine the level of permanency of the motor memory developed during acquisition (Kantak & Winstein, 2012), and 2) assess the strength of the error detection processes of the learner in the absence of KR as a function of the augmented information provided, or in some cases, not provided during the acquisition period. The predictions for the retention period of the experiment are discussed based on the test performed in the experimental conditions.

## **5.2 No-augmented sensory information test**

For the *no-augmented information test* it was predicted the no-feedback group would outperform the visual, auditory and visual-auditory group evidenced by lower |CE|, VE and AD scores (e.g., Coull et al., 2001). This prediction was based on the specificity of practice hypothesis which suggests motor learning is specific to the sources of afferent information (e.g., feedback) available during the acquisition period (Proteau, 1992). That is, the group that practiced with no augmented sources of feedback was predicted to outperform all other groups because they were tested in an environment very similar to what they practiced in (i.e., with no augmented sensory feedback and no-KR). It was thought groups who practiced with augmented sensory information during the acquisition period would experience decrements to motor performance and AD when the augmented sensory information was no longer available in the retention period. The |CE| and AD results failed to support this prediction as no group differences were found.

Based on AD scores, participants' ability to estimate their timing performance was similar regardless of whether or not motor performance was augmented with sensory information during the acquisition period. More specifically, it is possible the movement strategy for all groups was to focus primarily on the task-related sensory feedback naturally produced when the finger made contact with the TSD. Because the task goal was the same for all groups, the sensory feedback was available to all participants. Thus when auditory or visual augmented feedback was removed, learners were still able to make predictions that closely approximated their actual performance. Therefore, these results suggest the ability to estimate one's own performance was not dependent upon one source of augmented information a learner received during acquisition. Rather, we speculate the feed-forward (Schmidt, 1975) response of anticipating the expected sensory consequence allowed learners to extract important task-related sensory feedback to make timing predictions in the absence of KR during the retention period.

The findings from the no-feedback group who practiced in the absence of augmented sensory feedback are consistent with van Vugt and Tillmann (2015). Participants were to tap a 7-key sequence regularly in time under three conditions: synchronous-sound following keystroke, jittered-sound where the tone was presented after a random delay (10-190 ms) following keystroke, and a mute group where no keystroke-triggered sound was presented. van Vugt and Tillmann observed no improvements in tapping regularity for the mute group. Similar to the results of the present experiment, no improvements in timing error ( $|CE|$ ), and error-detection (AD) were evidenced in this test. Interestingly in the present test, the group who practiced with auditory feedback alone and in combination with visual feedback demonstrated more

consistent timing scores (lower VE) compared to the no-feedback group. These results suggest auditory feedback may be an important source of sensory feedback that leads to more consistent motor behaviour compared to not receiving any sources of augmented sensory feedback. That is, auditory feedback in performance may be necessary to make the initial learning of the task meaningful (Finney & Palmer, 2003). Additionally, lower VE scores may indicate a stronger capability to detect timing error. Learners may have become more sensitive to deviations of their movements such that their ability to detect whether their movement was too fast or too slow during the subjective estimation phase allowed them to create more consistent predictions.

### **5.3 Augmented auditory sensory information test**

For the *augmented auditory information test*, it was predicted the augmented auditory feedback group would outperform the visual and visual-auditory group evidenced by lower |CE|, VE and AD scores (e.g., Coull et al., 2001). This predication was not supported. The group who practiced with only auditory feedback did not demonstrate superior learning. Conversely, statistically significant differences were seen for the group who practiced under visual-auditory conditions as demonstrated by the lowest |CE|, VE and AD scores compared to the no-feedback group. The results from the present test suggest learners benefited from the combination of auditory and visual augmented information during acquisition in an auditory only test, compared to practicing with no augmented sensory information (Finney & Palmer, 2003).

Auditory feedback influences the motor response, often in a predictive manner during a feed-forward response (Drake, Penel & Bigand, 2000; Repp & Penel, 2004; Zatorre, Chen & Penhue, 2007). The present study required participants to learn a precise

timing goal of 2550 ms. It is possible the development of the error-detection mechanism in an environment that provides auditory feedback during practice created a stronger recognition schema as the auditory information provided more meaning to the task (Finney & Palmer, 2003), as audition has been found to be more sensitive to timing (Kanai, Lloyd, Bueti, & Walsh, 2011; van Vugt & Tillmann, 2015). On the basis of this evidence for auditory feedback, we did not find any significant differences for the group who practiced under auditory feedback alone. Furthermore, the condition that received both visual and auditory feedback during practice demonstrated superior timing accuracy and error-detection capabilities than the no-feedback group. Practicing in a multimodal sensory environment may have provided these learners with more meaningful sources of feedback to interpret their intrinsic feedback. Therefore, the provision of augmented sources of feedback, both sensory and KR during practice allowed the visual-auditory feedback group to develop a stronger motor memory of the motor task based on sensory redundancy. When one source of the augmented sensory feedback was removed for this test, learners in the visual-auditory group were still able to complete the task because the remaining source of augmented information available during acquisition remained in the delayed test.

It was also expected the augmented auditory sensory feedback for the no-feedback group would aid in decreasing timing error and improve error detection capabilities (e.g., Hoggan et al., 2008, 2009; Lee & Zhai, 2009). Therefore, it was predicted the no-feedback group would outperform the visual and visual-auditory group evidenced by lower |CE|, VE and AD scores (e.g., Coull et al., 2001). However, this prediction was not supported. The no-feedback group showed the largest timing error (i.e., |CE|) and error detection (i.e., AD) detriments compared to all groups. Specifically, statistically significant

differences were seen between the no-augmented feedback and visual-auditory feedback group as the no-augmented feedback group demonstrated greater timing error ( $|CE|$ ). A study conducted by Finney and Palmer (2003) suggested auditory feedback plays an important role in music memory performance. More specifically, practicing with auditory feedback develops a stronger music memory for later recall. Pianists were to perform a short music piece with or without auditory feedback from the piano keyboard during a defined practice period. Following an unspecified period at the end of practice, a delayed recall test was conducted. Participants were to perform the same music piece from practice with and without auditory feedback. They found the addition of auditory feedback during the recall test for those who practiced without auditory feedback did not improve the number of errors made. The results of the present experiment for the augmented-auditory sensory information test are commensurate with Finney and Palmer (2003) such that no performance benefits were seen when auditory feedback was present for the group who practiced without auditory feedback (i.e., no-feedback and visual feedback group). Although not statistically significant, mean scores showed the visual feedback group demonstrated the highest  $|CE|$  and second highest AD scores (behind the no-feedback group) indicating a detriment in performance similar to results found in the specificity of practice literature. Decrements in performance have previously been shown when visual feedback is removed for those who practiced under visual feedback conditions compared to groups who practice under auditory feedback conditions (Blandin et al., 2008; Coull et al., 2001; Proteau, 1992).

The results from the present delayed test also suggest the group who practiced under the visual-auditory feedback condition produced the least variability (i.e., VE) compared to the no-feedback group. Timing variability has been suggested to be an

equally important measure of motor performance as the progression of learning should lead to more consistent performance (Fischman, 2015; Schmidt & Lee, 2013). Our results suggest a benefit of augmenting auditory feedback to TSD performance during the practice period of a precise timing task, as it may provide more meaningful sensory information regarding the execution and correction of the timing of motor movements. Considering performance consistency (i.e., VE) in the context of timing movement goals allows us to speculate on the impact of decreased variability on subjective error-detection. In the present study, the visual-auditory feedback group demonstrated superior performance accuracy (i.e., lower  $|CE|$ ) and consistency in their timing performance. It is possible performing with low timing error may have resulted in more consistent timing movements thus leading to more accurate performance-estimations. From a practical point of view, correcting the timing movement in learners with high consistency should be easier. For example, learner A moves too quickly on all trials while learner B moves both too quickly and slowly on the trials. Due to the high consistency of learner A, it would be easier to employ a strategy to simply slow down their movements. However, it would be more difficult to instruct learner B to a more accurate movement due to the lack of consistency. That is, if learner B moves too quickly on their first movement and too slow on the second movement, it is difficult to instruct them to speed up or slow down because there is no consistent tendency towards overshooting or undershooting the target goal. Therefore, it is possible learners may become better at error-detection in timing movements with less movement variability because they are able to understand their intrinsic feedback to produce more consistent movements. The decrease in variability

allows them to more accurately “home-in” on the target goal time by making small adjustments in their movements.

#### **5.4 Augmented visual sensory information test**

For the *augmented visual information test*, no group differences were expected. Vision is noted as the most dominant source of sensory information used by a learner, therefore it was predicted all four groups will demonstrate similar performance as evidenced by |CE|, VE and AD (Blandin et al., 2008; Coull et al., 2001). This prediction was partially supported as there were no statistically significant group differences in terms of |CE| and AD. It may be argued the motor learning of this spatial-temporal timing task was driven by a combination of available kinesthetic feedback and the learners’ ability to see the finger move towards the button, as no significant group differences were found in |CE| and AD. In the earlier stages of practice, the spatial aspect of the task was learned first because the input of an incorrect sequence did not allow learners to provide a subjective estimate of their movement time. The motor control literature has suggested the human visuomotor learning process is responsible for correcting spatial error (Cheng & Sabes, 2006; Shadmehr, Smith & Krakauer, 2010). It is possible the no-feedback and auditory-feedback groups that were not provided explicit sources of augmented visual feedback (i.e., button colour change) were still able to learn the spatial aspect of the task because watching their finger touch the soft-key was enough visual feedback to understand which button was selected.

The HF/E literature provides an alternative interpretation regarding the use of augmented visual feedback. The change of colour or enlargement of button size upon keystroke on a TSD provides learners with *closure* (Harrison & Hudson, 2009). Closure

is the understanding the action has been completed. For example, we will continue to press a button on a TSD if we do not receive any type of sensory feedback as it becomes unclear whether the keystroke has been registered. However if the button changes colour or creates a sound following the keystroke, we understand our input has been registered therefore we can move on to create a subsequent motor action. The augmented sensory feedback in the form of a button colour change may have provided learners with visual closure. Additionally, the spatial aspect of the task may have been previously learned during the practice period therefore the visual colour change during this particular test may not have provided learners with further information to facilitate their subjective error-detection processes. No group differences in VE were predicted during this test. However, this prediction was not supported. Despite the absence of audition for the auditory feedback and visual-auditory feedback group, their timing variability was more consistent compared to the no-feedback group. Similar to results found in the two previous tests, the present results further strengthen the notion that auditory feedback may develop a stronger recognition schema for temporal movements. Regions of the brain said to be responsible for driving the timing mechanism in motor movements include the cerebellum, basal ganglia, and supplementary motor area (Zatorre et al., 2007). It has been shown the regularity of tapping is better with auditory feedback rather than visual or no feedback (Chen, Penhune, & Zatorre, 2008; Patel, Iverson, Chen, & Repp, 2005; Zatorre et al., 2007). Thus, it is possible the augmented auditory feedback allowed learners to associate the timing of their movements to a rhythmic beat to create more consistent movements in combination with their kinesthetic sensory system. That is,

intervals that sounded too long or too short could have informed the learner to speed up, or slow down for subsequent button pushes based on the strength of their motor memory.

### **5.5 Augmented visual-auditory information test**

It was predicted all experimental conditions would demonstrate similar performance as evidenced by |CE|, VE, and AD during the *augmented visual-auditory information test*. This prediction was not supported. Results from our study show the groups who received auditory feedback during practice (auditory and visual-auditory feedback groups) demonstrated the lowest |CE| and AD mean scores compared to the no-feedback group. The addition of auditory feedback for the visual-feedback group was not superior as no statistically significant differences between other groups were seen. Interestingly, adding visual and auditory feedback for the group who practiced without augmented sensory feedback was not beneficial. These results are similar to those found by van Vugt and Tillmann (2015). The no-feedback condition utilized in the present experiment, similar to their “mute” condition, did not show improvements during the retention period despite the addition of augmented sensory information. These results suggest the auditory feedback (e.g., sound) facilitated precise timing movements during the practice period allowing the learner to retrieve that motor response more effectively (Finney & Palmer, 2003; Ronsse et al., 2011). This provides further insight towards the idea learners find more meaningful information in auditory feedback when learning a timing task such that audition aids error detection and correction processes.

Further support comes from the VE scores as the auditory and visual-auditory feedback groups were more consistent than the visual and no-feedback groups. Not only does low variability indicate consistent motor movements but it also allows the learner to

easily “fix” their movement error (Fischman, 2015) because deviations from the target goal time are small (Schmidt & Lee, 2013). Moreover, it is possible participants learned to associate the sound between clicks with the expected sensory outcome of 2550 ms during practice. If the clicks between keystrokes sounded too long or too short, subsequent movements could be adjusted accordingly.

### **5.6 Subjective confidence ratings during the retention period**

In the present study, we asked participants to subjectively rate their confidence to accurately predict the success of the motor performance compared to the motor outcome. We expected the highest confidence ratings during each delayed retention test for the group(s) who practiced with the availability of that sensory modality during the acquisition phase. We did not find any significant group differences in any of the four delayed retention tests. Results from our study are inconsistent with previous research examining confidence measures when learners were required to provide a subjective estimation (e.g., Patterson et al., 2014). It is possible requiring learners to estimate their performance during all 100 trials of the acquisition phase increased their confidence to accurately predict their movement time compared to their actual movement time (e.g., Schmidt & White, 1972). Additionally, all groups were more confident based on their performance during acquisition to accurately predict their movement time in relation to the actual movement time during the delayed test period. Therefore whether or not task performance was augmented with sensory information, all groups self-reported confidence in their performance appraisal abilities.

### 5.7 Subjective workload ratings during the retention period

We measured subjective workload as it has been previously argued the subjective evaluation of the task difficulty may be just as important in terms of measuring usability as behavioural performance measures (Hart & Staveland, 1988). However, we found no statistical group differences amongst the conditions during acquisition. All groups performed the same timing task but with different sources of augmented information available. Learners did not have previous experience completing the timing task under different sensory modalities. Therefore it is possible the absence of knowledge regarding which experimental group they were randomized to did not influence their perceived subjective workload over the 100 trials of practice.

During the retention period, all groups performed each of the four tests. There were no significant performance differences between groups for each test. However, significant differences were found as a function of test as workload was rated highest in the *no-augmented sensory information test* compared to the *augmented-auditory sensory information test* and the *augmented visual-auditory sensory information test* respectively. These results suggest augmenting visual and/or auditory feedback decreases the cognitive workload. For example, Lee and Spence (2008) required participants to perform a driving avoidance task simultaneously to a phone entry task under a unimodal (visual only) or multimodal (visual-tactile, visual-auditory, and visual-auditory-tactile) feedback condition. They found subjective workload associated with the multimodal feedback task was significantly lower than the unimodal feedback. Furthermore, results from the present study are similar to Hoggan et al., (2008) such that subjective workload ratings

are significantly lower when augmenting sensory feedback to a TSD compared to a no augmented setting.

### **5.8 Preference for sensory modality**

Another subjective measure of interest was whether or not participants preferred a different modality compared to their practice condition during the retention period.

Although there were no significant group differences in  $|CE|$  during the *no- augmented sensory information test*, not one single participant in the study preferred completing this timing task without augmented sensory feedback. Daily interactions with TSD such as mobile phones have pre-programmed sensory feedback settings that indicate when a response has been made allowing for closure. Often times, the lack of sensory feedback on a TSD decreases user preference of the device (e.g., Hoggan et al., 2008, 2009).

Furthermore, we found all groups preferred performing the task with visual-auditory feedback over unimodal feedback (i.e., visual only and auditory only) which further suggests the importance of augmenting visual-auditory feedback to a TSD. In our daily interactions with TSD, we typically receive sensory feedback following a keystroke (i.e., colour change or click sound). Therefore, it is possible previous expectations regarding the sensory feedback available during the timing task resulted in a stronger preference for the multimodal augmented feedback.

## **CHAPTER 6: CONCLUSION**

### **6.1 Practical Implications**

We investigated different sensory modalities and how they differentially modulate error detection during a timing task on a TSD. In general, we found visual and auditory feedback in combination allowed for a stronger development of error detection capabilities. When one source of sensory feedback was removed, learners were still able to complete the task more accurately than the other groups. From a practical view, we may be accustomed to receiving visual feedback as well as auditory feedback from a touch screen ATM. However when we use a touch screen ATM in a noisy environment where auditory feedback is no longer available (e.g., amusement park or mall), we can still withdraw money because we have developed a perceptual sensory expectation when interacting with a TSD in combination with the available visual feedback. These results indicate practicing with a combination of sensory feedback allows for more effective error-detection and correction in situations where one source of sensory feedback is unavailable.

In the professional sporting world, franchises are constantly seeking new technologies to provide their team the winning edge (Sinelnikov, 2012). Coaches are integrating the use of touch screen tablets (e.g., Apple iPad, Microsoft Surface) to improve the performance of their players and winning success. However in noisy environments such as a stadium or arena, the salience of the auditory feedback may not be loud enough to overcome the yelling from the crowd but the coach may still execute the TSD with available visual feedback.

## 6.2 Limitations

To our knowledge, this was the first experiment to examine the contribution of various augmented sensory modalities for the development of subjective error detection accuracy when learning a soft-key pressing sequence on a TSD. However it should be noted a true control group was not used (i.e., no performance-estimation required and no augmented sensory feedback provided). Although this would change the purpose of the study, many studies have already identified the detriments to learning when learners do not provide subjective estimates prior to KR receipt (e.g., Guadagnoli & Kohl, 2001; Hogan & Yanowitz, 1978; Patterson et al., 2014; Sherwood, 2009, 2010). However, a control group may potentially elucidate whether learners in the no-feedback group relied on the interpretation of task-related sensory information (e.g., kinesthetic feedback) to become more proficient at error detection and correction.

We asked participants to provide their perceived subjective workload during the acquisition phase following the completed 100 trials. However because no group differences were seen, it would be of interest for future studies to measure perceived subjective workload following every 10 trials. This may provide a more sensitive measure of perceived cognitive workload throughout the practice period, rather than an overall measure. It would be important to identify what point during practice the task becomes too easy for the learner. The *challenge point framework* (Guadagnoli & Lee, 2004), suggests the task demands must optimally meet the skill level of the learner in order for learning to occur. Therefore measures of subjective workload over ten time points during the practice period, rather than one, may indicate a specific point in time during practice where the cognitive demands are low. Consequently, task demands can be

adjusted such that error-detection and correction capabilities of the learner are limited when the task becomes too easy.

### **6.3 Future Directions**

Young participants were utilized as participants in this experiment (ranging in age from 19-27) but it would be of interest for future research to determine whether visual-auditory feedback would be beneficial for older adults (ages 65 years and older; Hwangbo et al., 2013) as physical and cognitive abilities, such as pointing performance, change over time (e.g., Hertzum & Hornbaekm 2010; Murata & Iwase, 2005). It has been suggested older adults may benefit from multisensory feedback compared to younger adults when comparing button size and spacing (Hwangbo et al., 2013; Jin et al., 2007). To our present knowledge, the impact of multisensory feedback of completing the input of a numeric sequence to a target goal time has not been investigated in older adults. This is a particularly important issue as the ubiquity of TSD in public locations such as ATMs or self-serve checkouts continues to grow (Jin, Plocher & Kiff, 2007).

Much of the existing HF/E literature investigates tactile feedback alone, and in combination with either visual or auditory feedback (e.g., Hoggan et al., 2008, 2009; Hwangbo et al., 2013; Lee & Zhai, 2009) with results indicating the strong benefits of augmenting tactile feedback to a TSD. In this regard, it would be interesting to investigate the effects of minimizing the kinesthetic feedback available to the learner by placing an actuator on the monitor to add vibrations upon keystroke (e.g., Hoggan et al., 2008, 2009). It is possible in our present study learners relied on their kinesthetic feedback when completing the timing task, thus removing this source of sensory

feedback may provide further insight regarding how we learn to detect and correct both spatial and temporal errors when using a TSD.

The majority of our daily interactions with TSD are on a mobile touch screen phone (e.g., Apple iPhone). From a practical standpoint, we typically interact with handheld touch screen phones with our thumb when scrolling through pages, or selecting icons and buttons. Therefore it would be of interest to test learners with a similar protocol on a touch screen phone which may allow researchers to determine any motor learning advantages associated with the thumb.

#### **6.4 Conclusion**

The purpose of our study was to determine which sensory modality would best modulate subjective error-detection capabilities of learners performing a spatial-temporal task when using a TSD. During the delayed retention periods where participants performed the task under the same conditions they practiced in addition to three other sensory modalities, it was found in *some* cases auditory feedback may provide more meaningful information regarding the movement timing task. In this context, significant benefits in augmented auditory feedback were found during the *augmented-auditory sensory information test* and the *augmented visual-auditory sensory information test*. Furthermore, the present results also suggest practicing a timing task on a TSD with both visual and auditory information may have differentially impacted motor skill acquisition such that removal of one or both sources of augmented feedback did not result in a severe detriment to timing performance (i.e., |CE|) and error detection capabilities (i.e. AD). These results also show the importance of subjective measures (i.e., performance-estimation) of timing performance as an indicator of motor learning. In summary, the

present study showed the importance of multimodal augmented sensory feedback conditions to maximize error detection capabilities of the motor memory.

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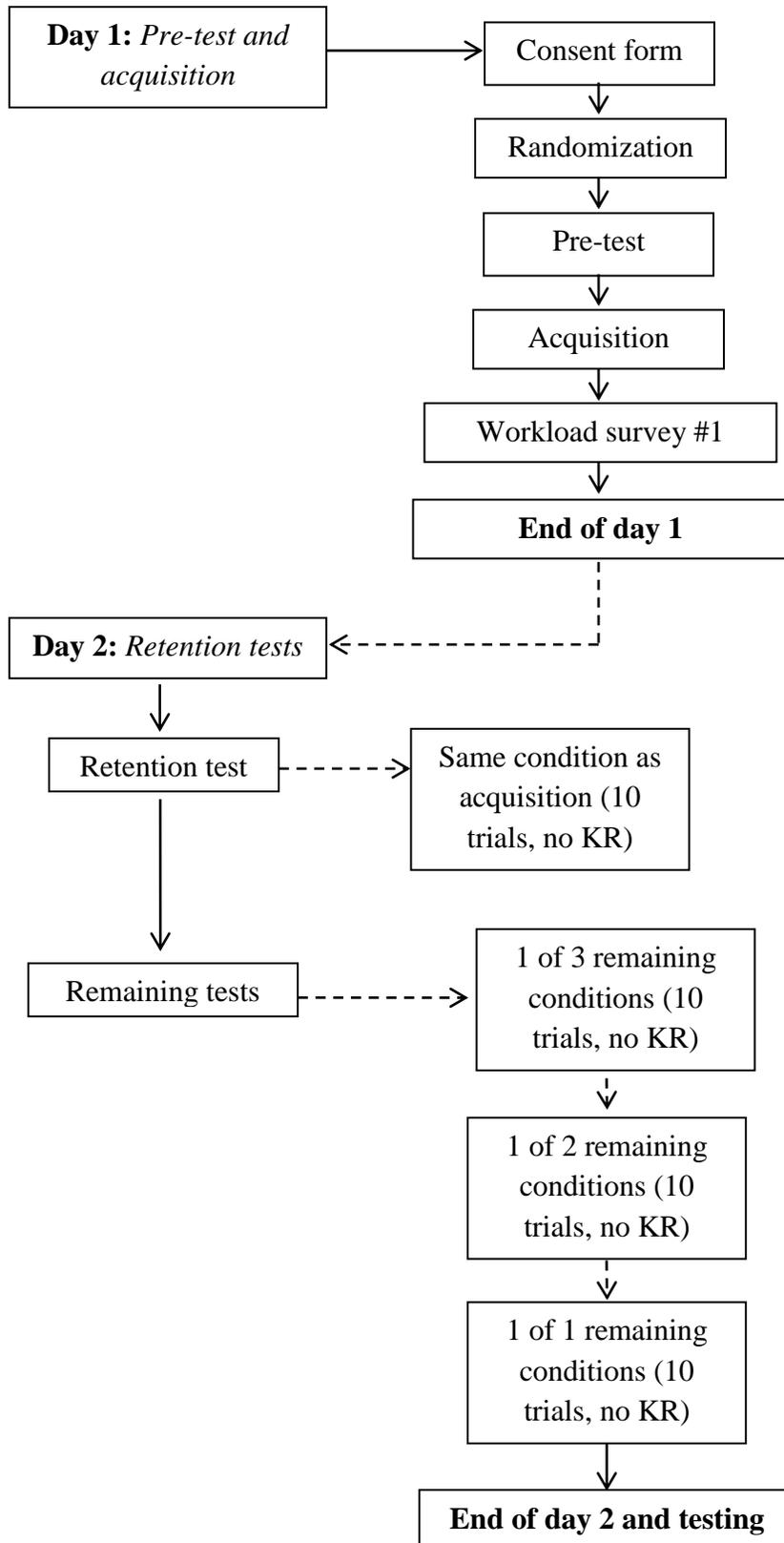
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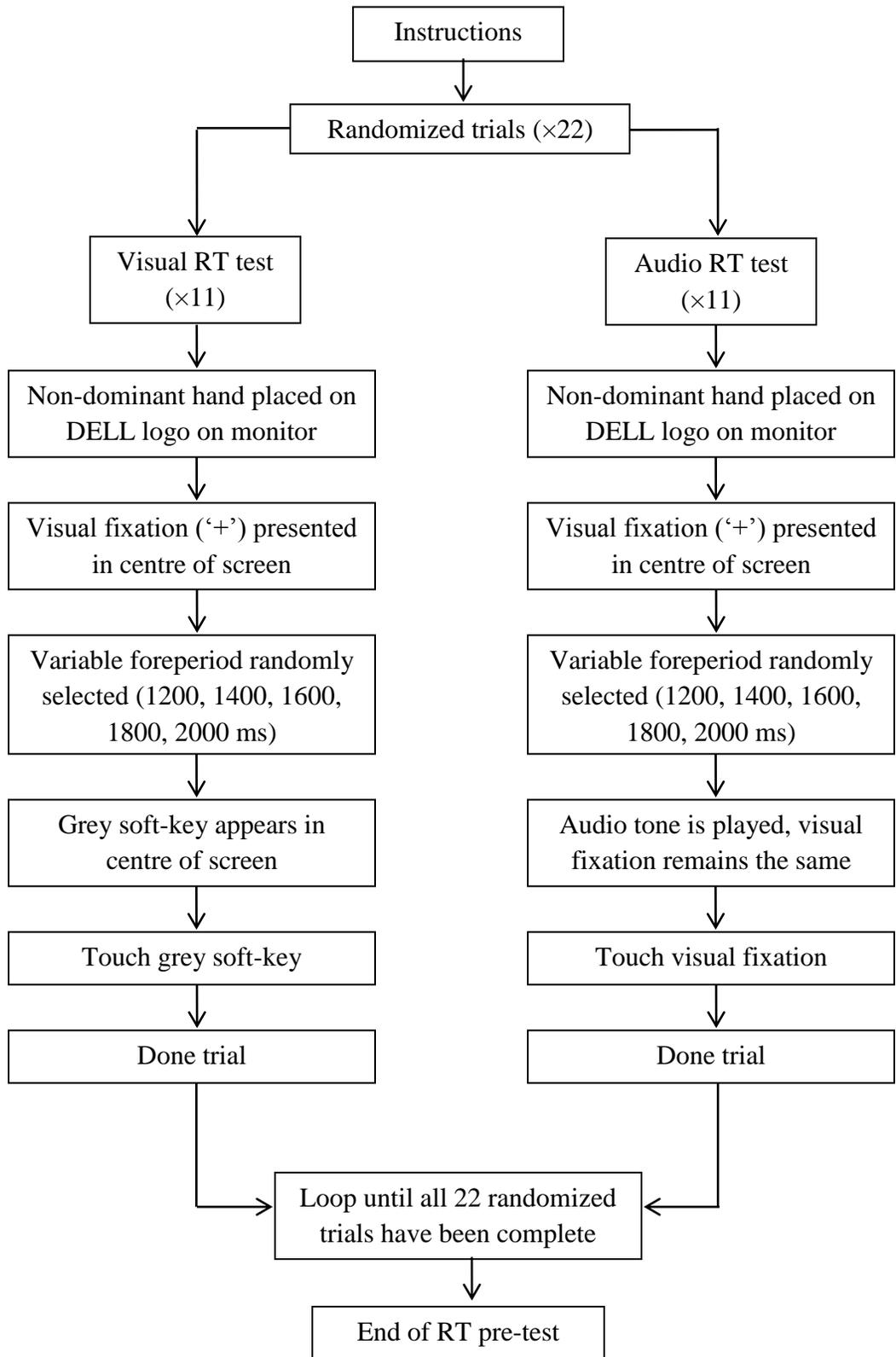
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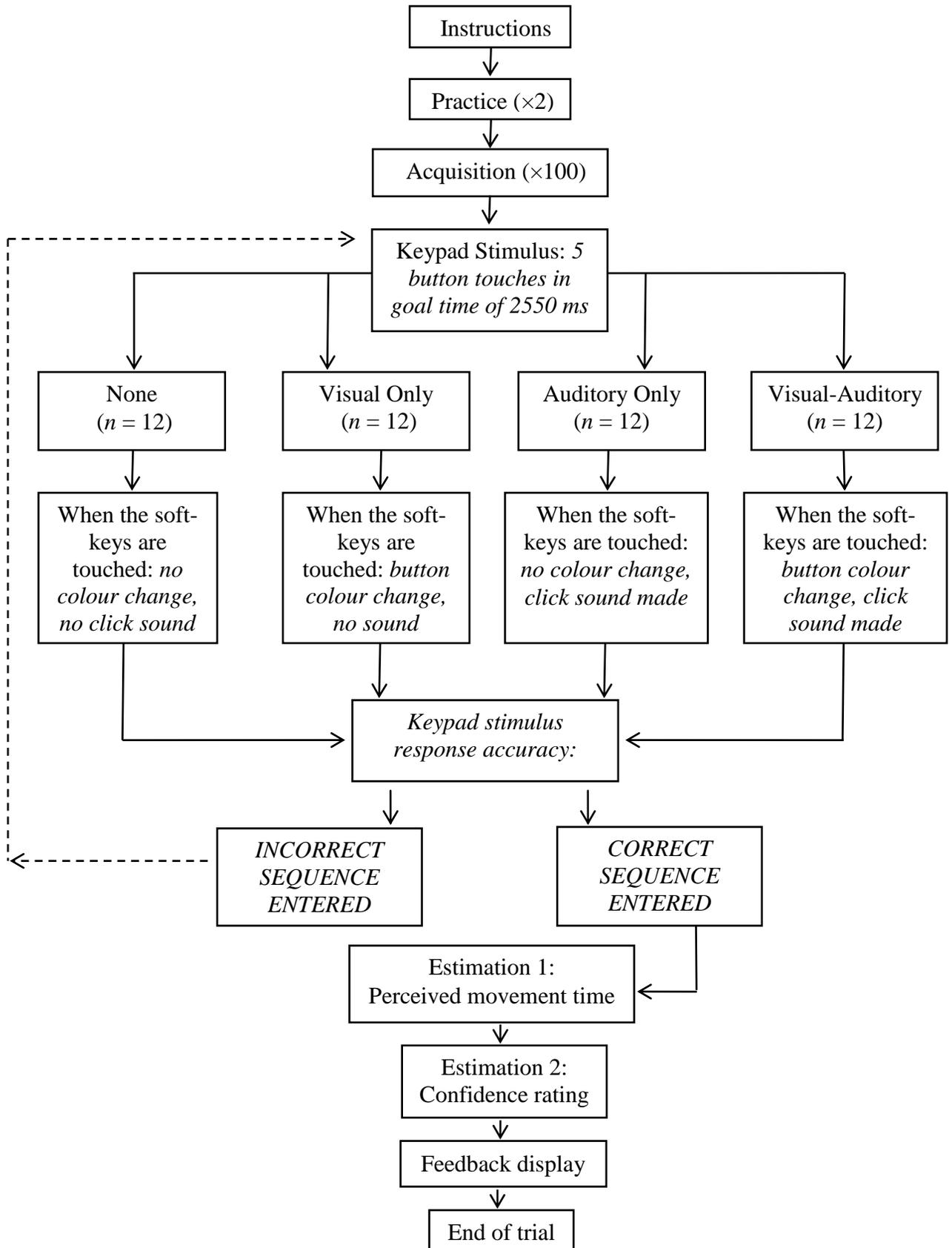
**Appendix A: Day 1 and 2 procedure timeline for all participants**



**Appendix B: Pre-test procedure for all participants**



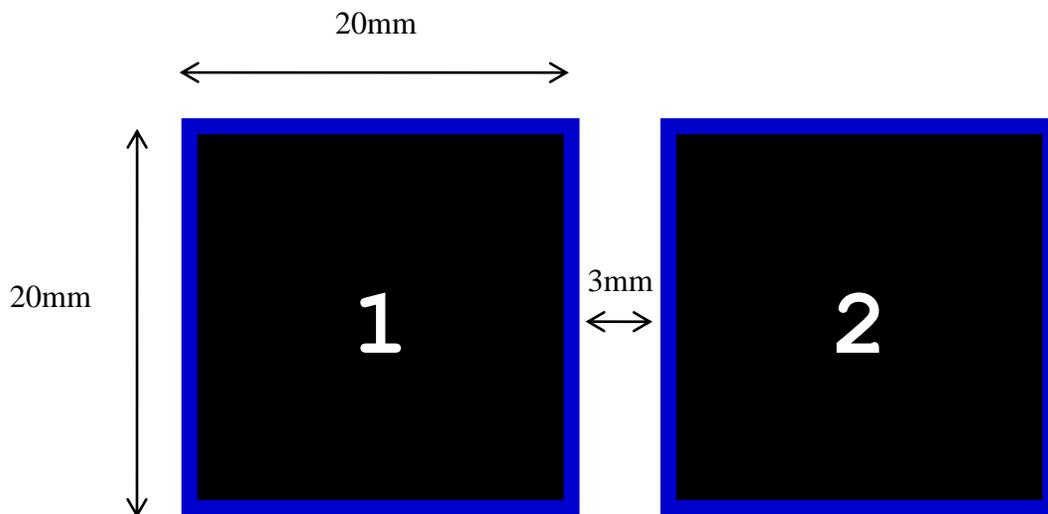
**Appendix C: Acquisition  
procedure for all participants**



**Appendix D: Keypad stimulus display**



**Appendix E: Individual soft-key dimension and spacing distance**



**Appendix F: Performance time estimation screen**

Enter your perceived movement time it took to complete the sequence.

— — — —

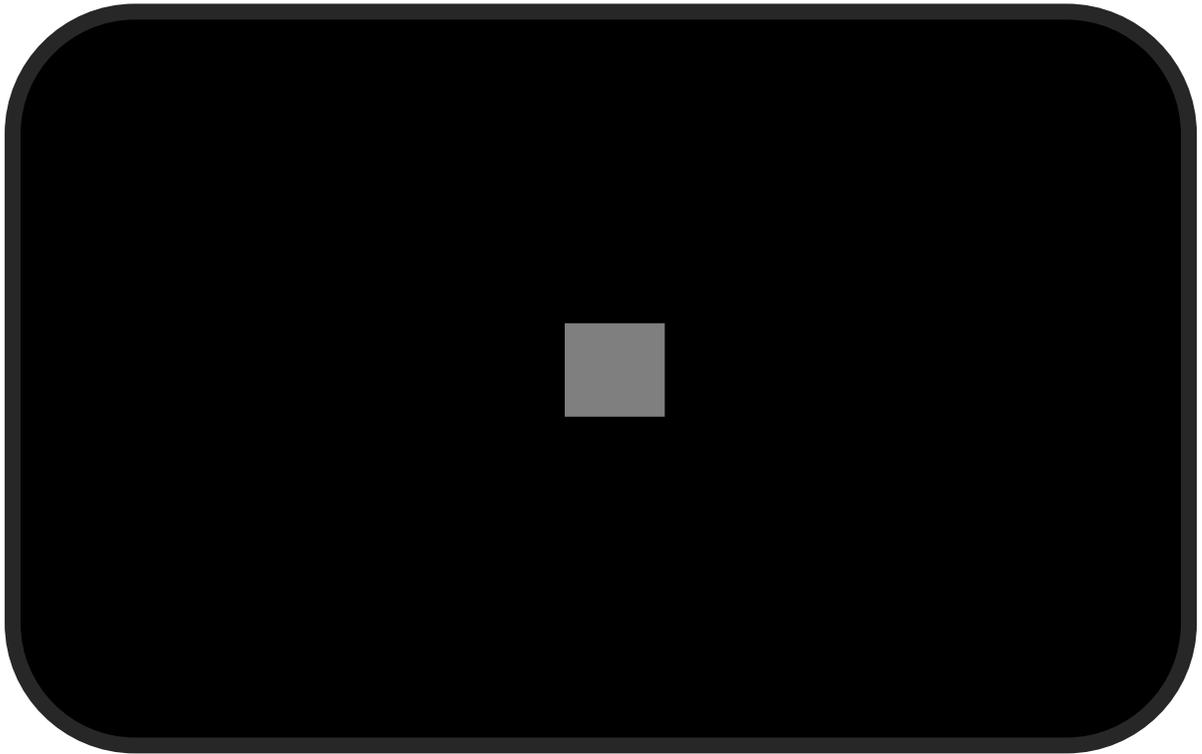
**Appendix G: Confidence rating screen**

How confident are you that your estimated movement time matches your actual movement time?

1 2 3 4 5

No confidence      Moderately confident      Completely confident

**Appendix H: Feedback display when correct sequence entered****Appendix I: Pre-test fixation**

**Appendix J: Pre-test visual stimuli****Appendix K: Cognitive workload**

*How much mental activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)?*

1 2 3 4 5

Low Moderate High

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**Table 1: pre-test means***Pre-test mean scores (standard deviations) in ms*

<b>Group</b>	<b>Auditory</b>	<b>Visual</b>
VF	739 (166)	861 (163)
AF	854 (172)	873 (145)
VAF	774 (134)	851 (153)
NF	768 (133)	873 (131)
Total	784 (153)	865 (144)

Note: visual feedback group (VF), auditory feedback group (AF), visual-auditory feedback group (VAF) and no feedback group (NF).

**Table 2: acquisition means***Acquisition mean scores (standard deviations) for absolute constant error, variable error, and absolute difference*

<b>Group</b>	<b>Block1</b>	<b>Block2</b>	<b>Block3</b>	<b>Block4</b>	<b>Block5</b>	<b>Block6</b>	<b>Block7</b>	<b>Block8</b>	<b>Block9</b>	<b>Block10</b>
<b> CE  (ms)</b>										
VF	388 (166)	362 (228)	323 (224)	284 (91)	262 (113)	248 (101)	253 (128)	247 (100)	310 (156)	285 (132)
AF	348 (108)	252 (90)	260 (152)	198 (113)	248 (149)	213 (129)	211 (176)	245 (167)	218 (132)	218 (118)
VAF	462 (364)	334 (168)	285 (195)	239 (146)	188 (74)	192 (93)	221 (110)	248 (110)	203 (146)	222 (128)
NF	394 (394)	339 (168)	367 (232)	277 (193)	287 (188)	280 (229)	308 (285)	268 (284)	288 (260)	266 (222)
<b>VE (ms)</b>										
VF	312 (132)	294 (150)	232 (94)	251 (75)	224 (102)	187 (61)	226 (132)	223 (101)	239 (112)	246 (153)
AF	356 (177)	207 (110)	242 (130)	172 (119)	265 (164)	146 (84)	130 (102)	236 (151)	214 (163)	209 (153)
VAF	264 (134)	304 (153)	216 (142)	209 (144)	125 (44)	138 (75)	177 (113)	244 (122)	119 (62)	164 (134)
NF	352 (235)	211 (121)	237 (187)	161 (58)	220 (165)	156 (69)	146 (76)	172 (112)	178 (89)	172 (82)

**AD (ms)**

VF	406 (212)	280 (139)	278 (117)	321 (196)	295 (157)	301 (169)	269 (132)	340 (173)	298 (141)	275 (120)
AF	297 (80)	272 (111)	229 (117)	166 (93)	195 (75)	261 (231)	177 (89)	211 (127)	240 (129)	187 (105)
VAF	266 (114)	272 (141)	272 (188)	253 (124)	265 (241)	185 (88)	193 (99)	228 (79)	194 (130)	232 (113)
NF	374 (148)	348 (149)	288 (192)	290 (147)	278 (131)	283 (132)	323 (191)	289 (186)	299 (251)	277 (182)

*Note: visual feedback group (VF), auditory feedback group (AF), visual-auditory feedback group (VAF) and no feedback group (NF).*

**Table 3: retention period means**

*Retention period means (standard deviations)*

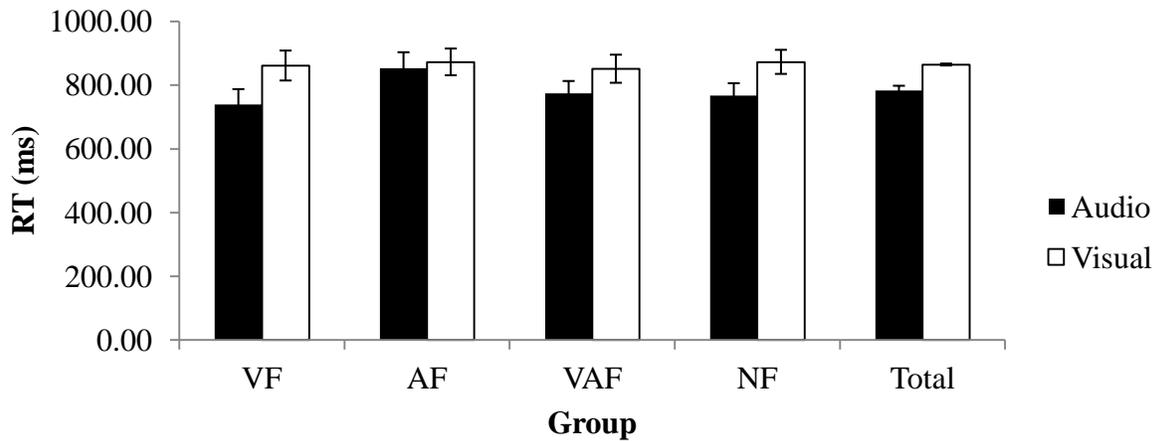
	<b>nSI</b>	<b>aSI</b>	<b>vSI</b>	<b>vaSI</b>
<b> CE  (ms)</b>				
VF	354 (196)	383 (137)	368 (126)	366 (178)
AF	356 (227)	359 (169)	310 (189)	238 (105)
VAF	316 (134)	236 (113)	302 (142)	262 (93)
NF	346 (186)	398 (161)	352 (208)	428 (161)
<b>VE (ms)</b>				
VF	171 (57)	171 (75)	206 (104)	177 (73)
AF	152 (83)	188 (90)	157 (82)	117 (47)
VAF	157 (112)	149 (67)	144 (85)	157 (50)
NF	295 (177)	357 (176)	313 (210)	218 (73)
<b>AD (ms)</b>				
VF	329 (158)	388 (158)	348 (100)	414 (190)
AF	314 (183)	328 (161)	315 (145)	271 (189)
VAF	281 (129)	237 (127)	321 (178)	271 (136)
NF	346 (180)	433 (180)	378 (236)	567 (292)

*Note: no augmented sensory feedback test (nSI), auditory augmented sensory feedback test (aSI), visual augmented sensory feedback test (vSI), visual-auditory augmented sensory feedback test (vaSI)*

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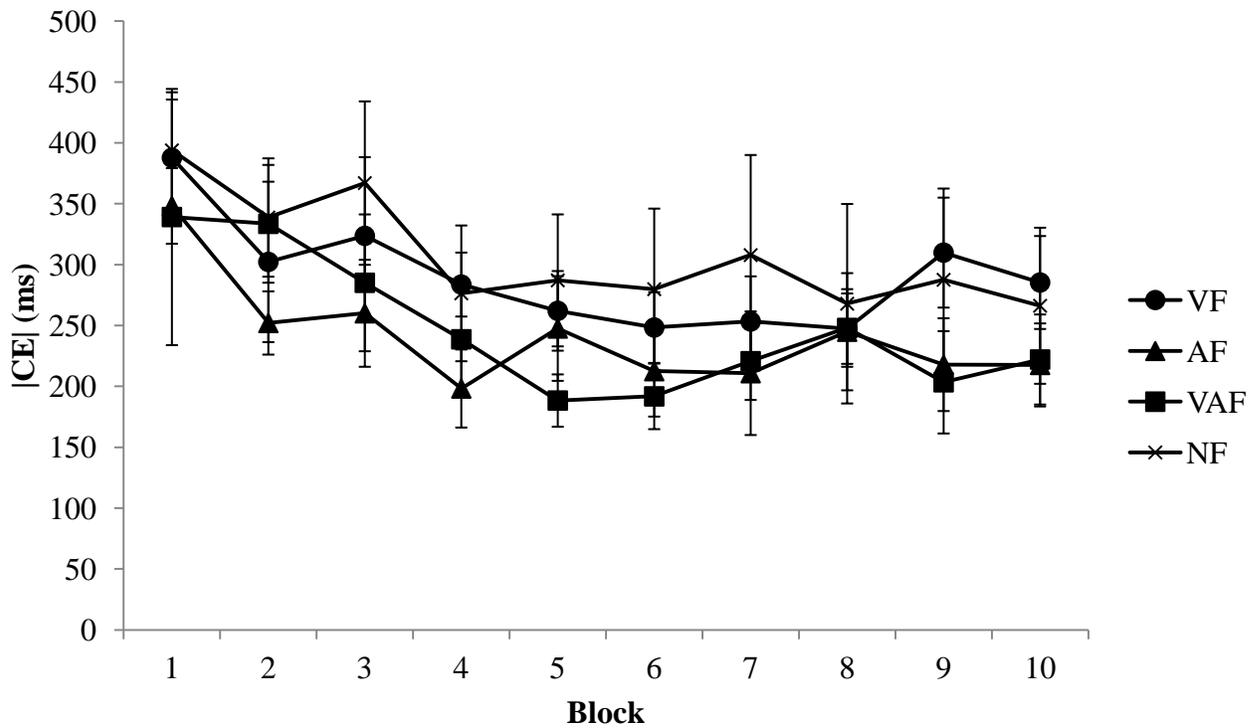
**Figure 1: pre-test means**

*Pre-test reaction time means for visual feedback group (VF), auditory feedback group (AF), visual-auditory feedback group (VAF) and the no feedback group (NF).*



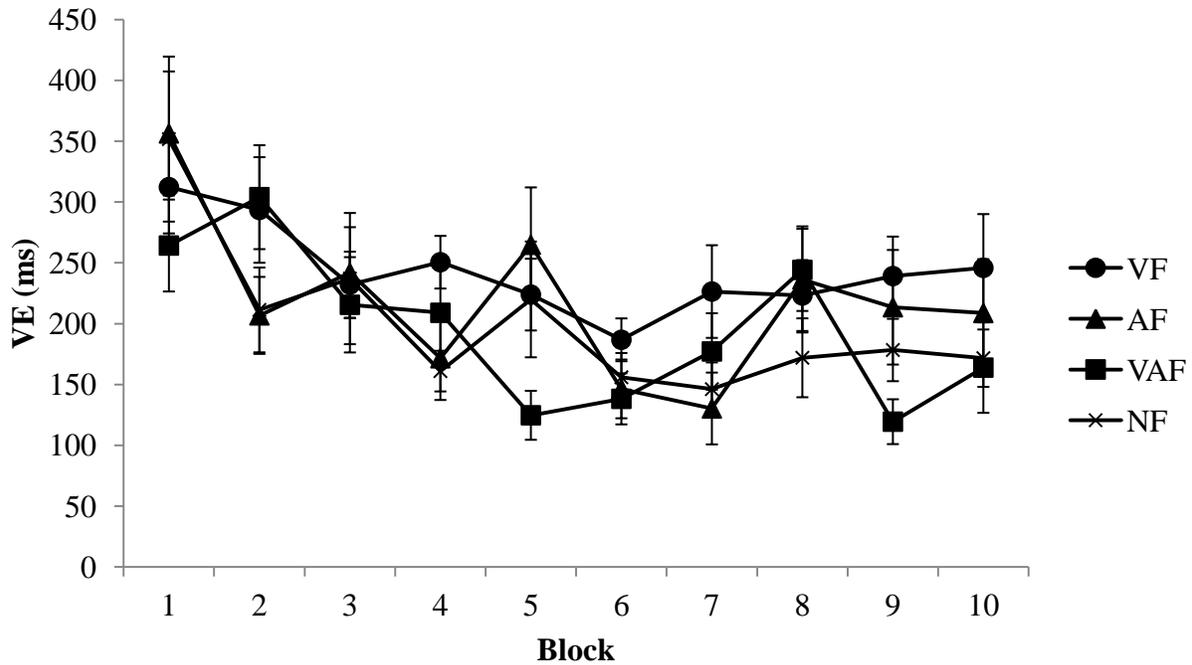
**Figure 2: absolute constant error (acquisition)**

*Acquisition absolute constant error ( $|CE|$ ) means for the experimental groups for 10 blocks of 10 trials in milliseconds (ms)*



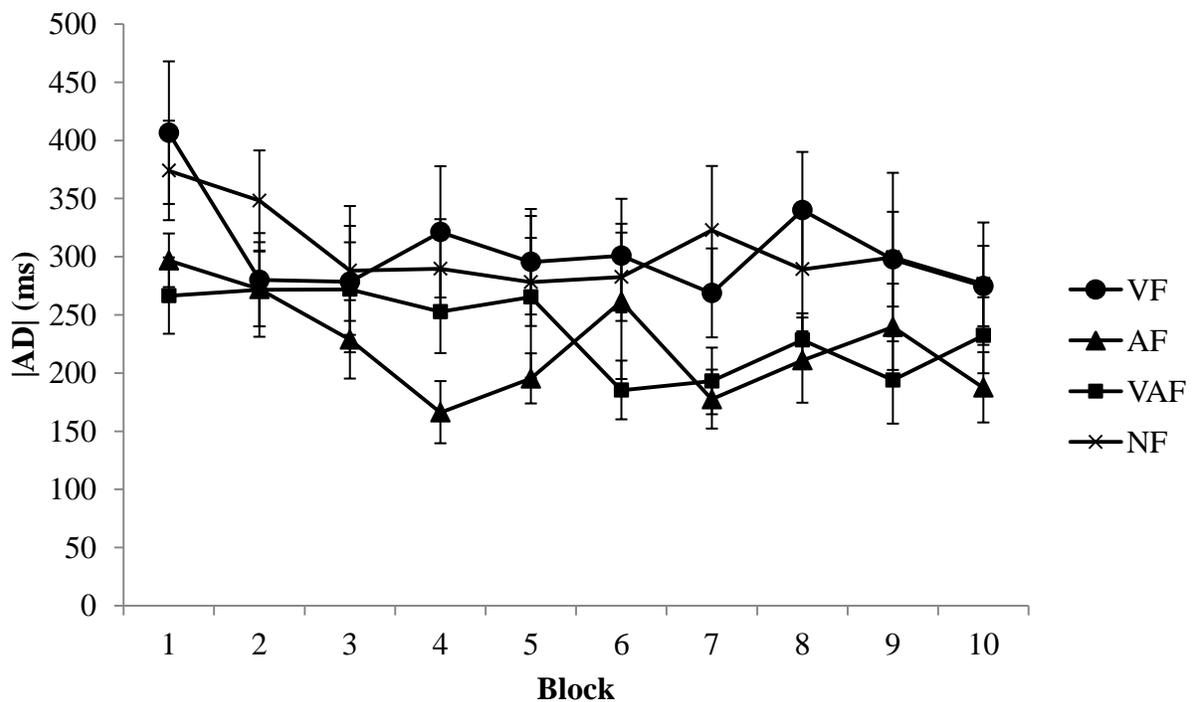
**Figure 3: variable error (acquisition)**

Acquisition variable error (VE) means for experimental groups over 10 blocks of 10 trials in milliseconds (ms)



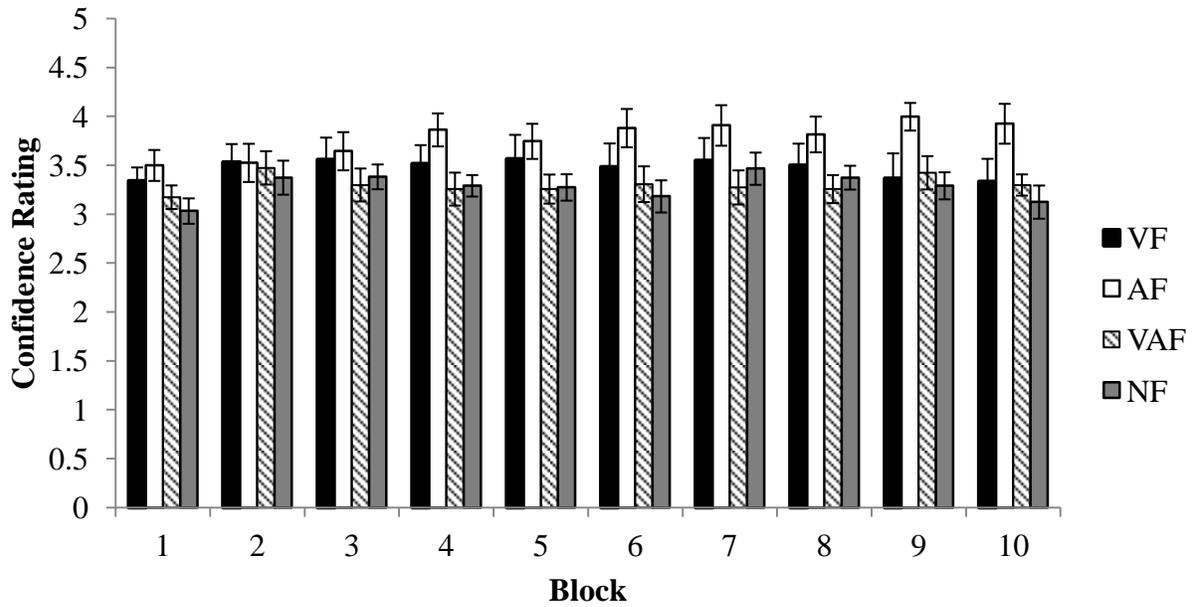
**Figure 4: absolute difference (acquisition)**

Acquisition absolute difference [AD (performance time – estimated time)] means by group over 10 blocks of 10 trials in milliseconds (ms)



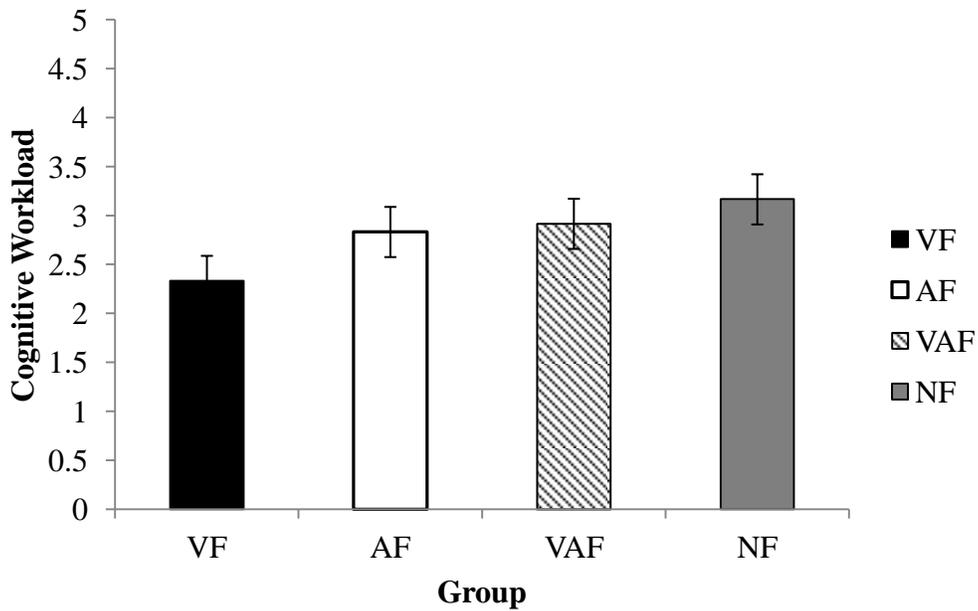
**Figure 5: confidence ratings (acquisition)**

*Acquisition confidence ratings by experimental group over 10 blocks of 10 trials on a 5-point scale*



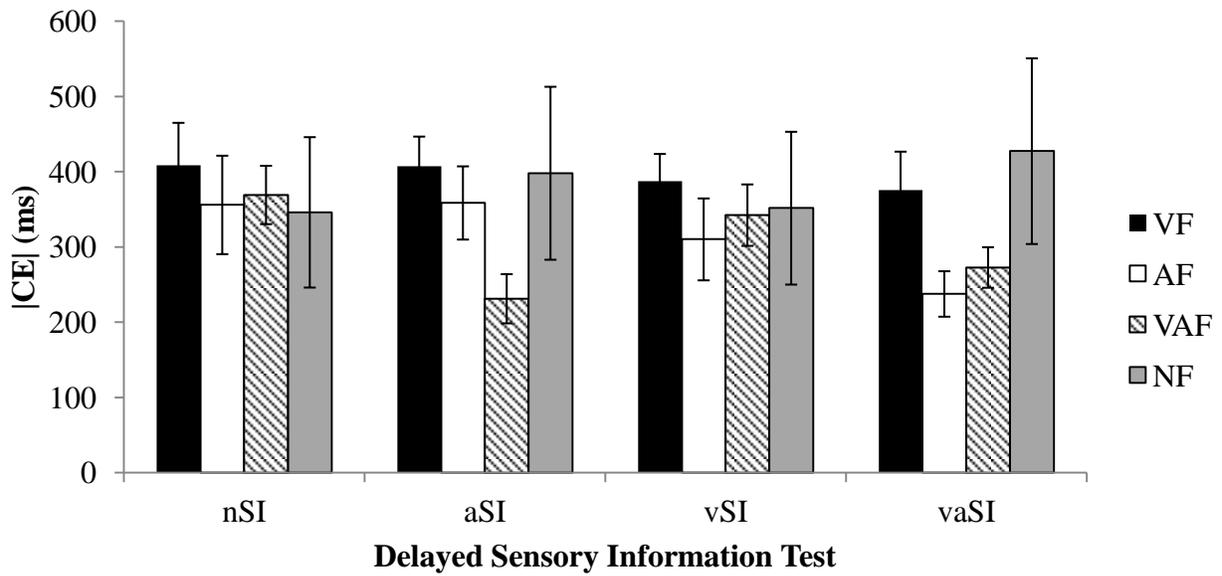
**Figure 6: cognitive workload (acquisition)**

*Acquisition subjective cognitive workload ratings for experimental groups over 10 blocks of 10 trials on a 5-point scale*



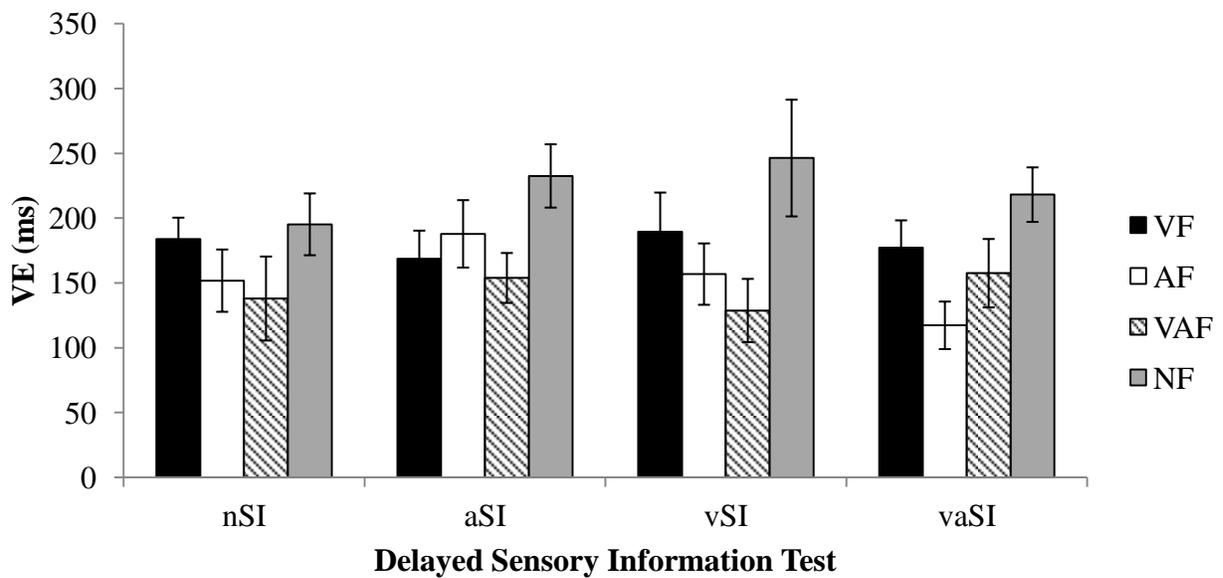
**Figure 7: absolute constant error (retention and delayed tests)**

*Retention and delayed tests: absolute constant error ( $|CE|$ ) means by type of test. No augmented sensory feedback (nSI), auditory augmented sensory feedback (aSI), visual augmented sensory feedback (vSI), and visual-auditory augmented sensory feedback (vaSI)*



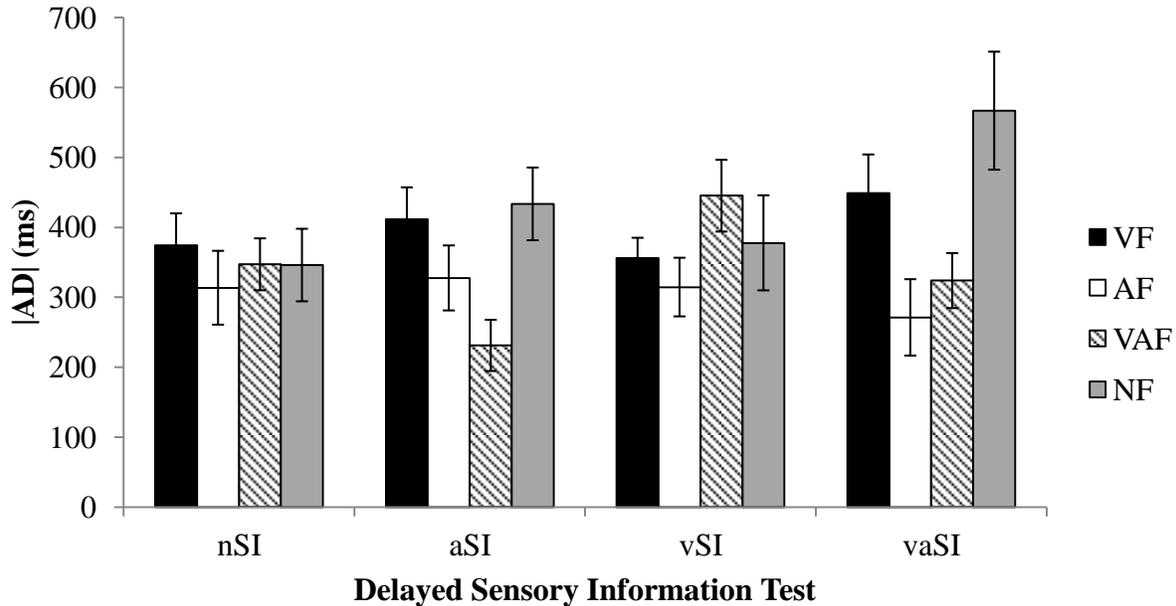
**Figure 8: variable error (retention and delayed tests)**

*Retention and delayed tests: variable error (VE) means by type of test. No augmented sensory feedback (nSI), auditory augmented sensory feedback (aSI), visual augmented sensory feedback (vSI), and visual-auditory augmented sensory feedback (vaSI)*



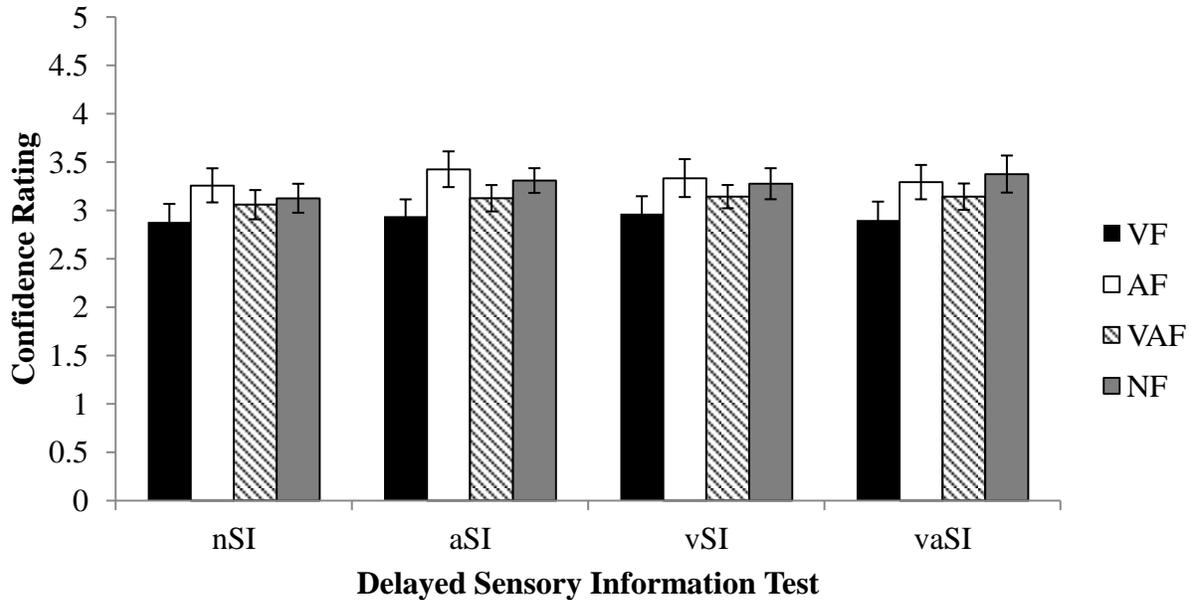
**Figure 9: absolute difference (retention and delayed tests)**

*Retention and delayed tests: absolute difference [AD (performance time – estimated time)] means by test in the delayed retention period. No augmented sensory feedback (nSI), auditory augmented sensory feedback (aSI), visual augmented sensory feedback (vSI), and visual-auditory augmented sensory feedback (vaSI)*



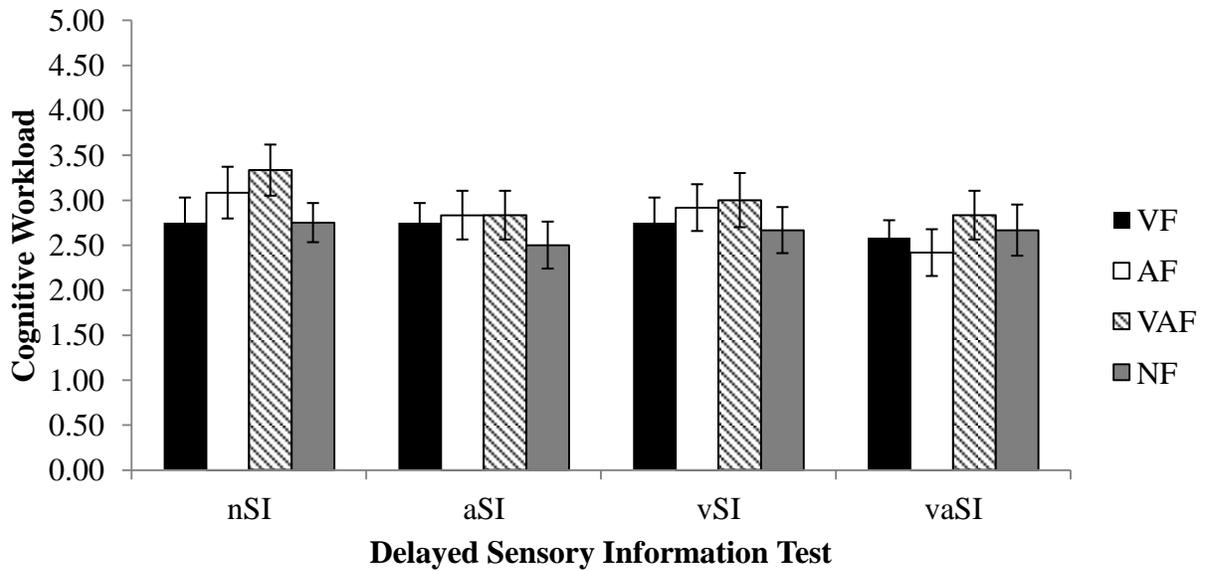
**Figure 10: confidence ratings (retention and delayed tests)**

*Retention and delayed tests: confidence ratings for experimental conditions as a function of test in the delayed retention period.*



**Figure 11: subjective cognitive workload (retention and delayed tests)**

*Retention and delayed tests: subjective cognitive workload ratings by experimental condition over 10 blocks of 10 trials on a 5-point scale*



**Figure 12: sensory modality preference**

*Sensory modality preference following the completion of 40 trials during the retention period*

