OPTIMIZING THE CONTROL OF HIGH INDEX OF DIFFICULTY MOVEMENTS: AN INVESTIGATION OF FEEDBACK INFLUENCE ON YOUNG AND ELDERLY MOTOR BEHAVIOR

A Dissertation

by

JASON BAXTER BOYLE

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Chair of Committee,	Charles H. Shea
Committee Members,	David L. Wright
	John J. Buchanan
	James W. Grau
Head of Department,	Richard B. Kreider

May 2014

Major Subject: Kinesiology

ABSTRACT

Three experiments were conducted to not only further the understanding of previously seen enhancements to goal directed movements following sine wave tracking, but also to investigate if this effect is present following training in an active elderly population.

The purpose of the first experiment was to investigate if a template constructed from recorded Fitts target task limb displacement would provide performance enhancements previously seen following sine wave tracking. Participants (master) where either asked to complete 45 acquisition trials of a Fitts target task or track a sine wave template. The recorded displacement of their performance made up the acquisition templates for two other participant (yoked) groups. Following acquisition, all participants were asked to complete 9 trials of a Fitts target task. The results of this study concluded that participants in both the sine tracking groups showed enhanced performance compared to the Fitts groups. Movement time, time to peak velocity, and endpoint variability were similar for the two sine groups indicating not only faster but more harmonic motion than for the Fitts groups that practiced under the Fitts conditions.

The purpose of the second experiment was to determine if sine wave tracking with amplitude different from that used on the test will result in equally effective transfer to a Fitts task. Participants were assigned to tracking a sine wave template with amplitudes of 16^o or 24^o or a Fitts task condition with amplitudes of 16^o or 24^o. Following 45 acquisition trials, all participants were tested under Fitts task conditions with amplitude=16^o. Results demonstrated that participants who tracked the sine wave templates of 16^o and 24^o showed enhanced performance and were equally effective in performing the 16^o Fitts task.

The purpose of the third experiment was to determine if sine wave tracking in an active elderly population would result in decreased movement time without an increase in error when later transferred to a Fitts target task. Participants (elderly, young) where either asked to complete 45 acquisition trials of a Fitts target task or track a sine wave template. Following acquisition, all participants were asked to complete 9 trials of a Fitts target task. The results of this study concluded that participants in both the sine tracking groups (elderly, young) showed enhanced performance compared to the Fitts groups with respect to their age.

Taken together the present experiments not only adds to the extensive literature related to speed-accuracy trade-offs, but presents a novel approach to re-thinking the way typical motor behavior is enhanced at tasks of higher difficulty now and throughout the lifespan.

DEDICATION

This work is dedicated to the driving force of my world, my wife Krystal and sons Brody, Collin and Matthew. The absolute most important thing in life is family. God has truly blessed my life by placing all of you in it.

ACKNOWLEDGMENTS

I would like to earnestly thank my advisor, Dr. Charles Shea for mentoring me throughout these years. I am forever indebted to you for taking a chance on me so long ago. I would also like to thank Dr. David Wright, Dr. John Buchanan and Dr. James Grau for sitting on my committee, and providing me with valuable research tools from personal discussions and lectures.

Thank you to my parents, Marti and Dr. Larry Boyle. You have been a never failing rock of support, advice and love throughout this journey.

Most of all I would like to thank my wife, Krystal Boyle. You are the most unselfish, gracious, beautiful, caring and amazing women I will ever know. I love you and thank you for all you have done and continue to do throughout this journey. Without you, these pages are blank.

TABLE OF CONTENTS

Page

CHAPTER

CHAPTER

LIST OF FIGURES

CHAPTER I

INTRODUCTION

In many daily activities, movement of the limbs, for example extending an arm to grasp a cup, requires a trade-off of speed for accuracy depending on the difficulty of the task (for review see Elliot et al., 2010). In the late 1800's it was well documented (Woodworth, 1899) that increased speed of the limb resulted in decreased accuracy, but it wasn't until over 50 years later that this idea would be most notably advanced (Fitts, 1954). Today, one of the most highly cited accounts of this speed-accuracy trade-off comes from a series of experiments performed by Fitts (1954). In his seminal work, Fitts noted that when participants attempted to move back and forth between targets, increases in movement amplitude (A) and/or in target width (W) resulted in increased average movement time (MT) due to increased attentional demands. Following Shannon's information theory (1949), Fitts developed an index of difficulty (ID) which he theorized was a result of the number of bits of information needed to be processed to efficiently generate the desired level of precision required to successfully move between the targets. Although there are many variations present today (Crossman, 1956; Guiard, 2009; Meyer et al., 1988), one of the most widely used calculations of ID can determined by the equation $\mathrm{Log}_2\,(2A/W)$, where A represents the amplitude of the movement measured from one target center to the other and W represents the corresponding width of the target area in the direction of the movement. Therefore, MT across a range of IDs can be characterized by the equation $MT = a + b\,(ID)$.

Target directed movement of the limbs, whether discrete (Fitts & Peterson, 1964; Meyer et al., 1988) or reciprocal (Adam & Paas, 1996; Boyle & Shea, 2011; Guiard, 1997; Kovacs, Buchanan, & Shea, 2008; Mottet & Bootsma, 1999) traditionally exhibit a speed-accuracy trade-off of motor control as difficulty increases (Fitts, 1954; Woodworth, 1899). Namely, as the difficulty of the task increases, performers must adjust movement time in order to accurately strike the target area. In relation to the control processes and kinematic variables related to this motor output, studies have consistently revealed that as movement time decreases, the proportion of time utilized in the acceleration stage of the movement diminishes. This unequal shift in movement components indicates that as difficulty increases, movement control shifts from preplanned, more cyclical control to online, more discrete control (e.g., Buchanan, Park, & Shea, 2006).

In a recent experiment by Boyle, Kennedy, and Shea (2012a), a Fitts' group were asked to practice an elbow extension/flexion reciprocal Fitts' task. Participants were instructed to move as fast yet accurately as possible between two displayed targets. Conversely, a Sine group during acquisition was instructed to track a sign wave template in the projected visual display. The template was constructed with a period that resulted in total times comparable to that used by participants in the Fitts' group. Similar to the Fitts group, participants were instructed to track the path presented by the template by extending and flexing the lever about their elbow. If participants were successful they would execute a harmonic (smooth, symmetrical acceleration and deceleration phases) that would also reverse in the target area, even though the target lines were not present in the display. Because of the cyclical nature of tracking the template the authors termed the sine wave as an "optimized" movement path. Following Test 1 in which the respective groups were tested under the conditions they experience during acquisition, both groups were then asked to perform Test 2 under the Fitts' conditions. The results revealed that the Sine group not only produced lowered movement times on Test 2 compared to the participants who trained under the Fitts conditions during acquisition, but kinematic components of accuracy (i.e. endpoint variability and hit rates) were upheld. In other words, while movement time was reduced, accuracy (hits, endpoint variability) remained high and % time to peak velocity increased leading the authors to conclude the Sine participants adopted a more harmonic/cyclical movement control strategy.

Although fascinating, the sine wave protocol is still not fully understood. It is important to note that the period of the sine wave was set to match the total time observed in the Fitts' group (Boyle et al., 2012a). However, when the Sine group was transferred to the self-paced Fitts' task the participants moved significantly faster than they were required to move given the sign wave template and the movement time under this condition was strikingly faster than that achieved by the participants in the Fitts' group that trained under the test conditions. The fact that the Sine group altered their movement time suggests that they did not learn a time dependent control strategy but could rescale their movements when provided the opportunity. However, what was it about the sine wave training that promoted this flexible form of control? A basic question that could be asked is was it the specific sine wave used in the study that promoted the enhancement, or rather could simply tracking a variation of the previous sine wave promote the same form of control? Indeed future experiments allowing the exposure to different forms of sine wave training would further the understanding of this movement enhancement. One potential way to investigate this enhancement would be a presentation of traditional Fitts movement traces to high ID targets (e.g. low % time to peak velocity, large dwell times) in a similar template format. Movement enhancements following what we would describe as an "un-optimized" template would lead to the conclusion that simply following a template enhances movement and the previous results were not due to the specific "optimized" design sign wave template. Also, the fact that the movement amplitude in Boyle et al., 2012a remained constant across practice/tests does raise the possibility that the learned movement strategy was specific to the amplitude experienced while following the sign wave template. Alternatively, participants in the Sine group may learn a more generalizable control strategy that would allow them to not only scale movement time but also amplitude. If the sine wave protocol does result in a generalizable movement representation it would greatly increase the utility of this training protocol not only for speed-accuracy trade-off studies, but research investigating goal directed movement throughout specific populations. Finally, participants in the Boyle et al., (2012a) study ages only ranged from 18 to 25. Research has repeatedly shown (for review see Ketcham et al., 2002) that elderly performance on goal directed target tasks (i.e. Fitts tasks) show decreases in kinematic variables that could potentially be specifically enhanced in this design (e.g. faster movement time, less dwell time, higher % time to peak velocity). Further research of the sine wave protocol could investigate if different populations in age produce the same motor enhancement previously seen, or if the results are specific to an age range.

Experimental Hypothesis

Three experiments are proposed, which were designed in an attempt to not only further the understanding of previously seen enhancements to goal directed target movement following sine wave training, but also investigate whether sine wave training results in lower movement times without increasing error in an active elderly population.

Experiment I was designed to replicate the findings seen in Boyle et al., 2012a and to determine if training with a template constructed from typical Fitts performance results in lower movement time without increasing error upon transfer to a Fitts target task. The benefit of this design allows participants to physically interact with the same motion Fitts performers undergo and empirically examine if presenting this task as a template and not dual targets, results in lower movement time on the transfer test, or if the template used to guide the movement requires deliberate design to influence control strategies.

Experiment II was designed to determine if sine wave tracking with an amplitude different from that used on the test will result in equally effective transfer to a Fitts task. The specificity of learning hypothesis proposes that during practice, participants select the source or sources of feedback that they feel ensure optimal performance (Blandin, Toussaint, & Shea, 2008; Proteau, 1995). Thereafter, participants selectively process this information while refining their performance and ignore other sources of information provided in the display. Showing effective transfer with lowered movement time after tracking a sine wave of differing amplitude would further the original conclusions that tracking the sine wave promotes a generalizable flexible form of cyclical control.

Experiment III was designed to investigate if sine wave training results in lowered movement time without increasing error in an active elderly population. Research has repeatedly shown that elderly participants compared to young participants display not only slower movement times (high values of movement time) in Fitts tasks, but also exhibit distinct differences in select kinematic components of the movement structure (Ketcham et al., 2002). These kinematic components (e.g., peak velocity, percent time to peak velocity, dwell time, endpoint variability) are directly influenced following sine wave training in young participants and could possibly enhance select components in an elderly population, leading to a change in motor performance.

CHAPTER II

LITERATURE REVIEW

Motor Behavior Question

Humans utilize and coordinate the limbs in a variety of manners related to specific goal outcomes. The way we interpret, plan, integrate and execute goal directed movements are a few of the key areas of study in the field of motor neuroscience. For well over 100 years, research examining goal directed movements of the limbs has well documented that reciprocal and/or discrete aiming movements to a target are constrained by what has come to be known as a speed-accuracy trade-off. This tradeoff essentially means that target endpoint accuracy decreases and/or endpoint variability increases with faster movement speed; requiring the performer to slow down when greater target endpoint accuracy is required. Kinematic components of these movements (e.g., velocity, acceleration, dwell time) provide a window into the way our neuromuscular system organizes from the simplest to the most complex limb movements. Although a great deal of research has examined speed-accuracy trade-offs from multiple perspectives, recently studies (Boyle et al., 2012a; Boyle et al., in press; Boyle et al., in revision) have shown that the way we train or present information may have an impact on what we consider typical speed-accuracy trade-off motor behavior.

Speed-Accuracy Trade-off

Initially, Woodworth (1899) proposed a two component model of goal directed movement with the first component involving an initial “ballistic” phase driving the movement toward the target followed by a second component involving a slower closed-loop “homing-in” phase governing the approach to the target. This idea proposes that the initial “ballistic” impulse directs the limb toward a target and current control initiates small submovements to maintain accuracy about the target area. In Woodworth's seminal work, participants performed a repetitive line drawing task between two targets, with the speed of their movements paced by a metronome. In this study, metronome speed, distance between targets, eyes open/closed and right/left hand control were examined. Participants were instructed to repeatedly trace a line of constant and variable distance while the metronome systematically became faster or slower. Following its completion, Woodworth's results pointed to one of the first documented relationships regarding a loss in accuracy as speed of the effector is increased.

Over fifty years following Woodworth's seminal work, one of the most well documented quantifications of the speed-accuracy trade-off relationship has come to be known as Fitts Law (Fitts, 1954). In Fitts seminal study, participants' were asked to rapidly alternate tapping the tip of a stylus on two defined target areas continuously. The two target areas had a width of correct response (W) separated by a defined amplitude (A) measured from the center of each target center. Participants were instructed to continuously tap the tip of the stylus in the target areas as rapidly as they could, while making sure they accurately struck within the target. Following the completion of his work, mathematical analysis of the effect of movement A and W on movement time was used to form an index that Fitts explained encompasses the difficulty of goal directed target movement. This index, although it has been questioned recently as to its appropriate description (Boyle & Shea, 2013; Guiard & Olafsdottir, 2011), has come to be most commonly referred to as the index of difficulty (ID). The index is calculated by the equation $ID = \mathrm{Log}_2\ (2A/W)$ and both A and W, which explained previously, are independent variables that when manipulated decrease or increase the value of ID, which in turn influences MT as represented in the equation $MT = a + b\ (ID)$

(for alternate calculations see Crossman, 1956; Mackenzie, 1989; Meyer et al., 1988). The a and b represent empirical constants of intercept (a) and slope (b). The comparison of MT to ID reveals what many consider the relationship that captures the essence of the speed-accuracy trade-off, the linear slope of movement time as related to difficulty adjustments. According to Fitts' (1954) original formulation of the speed-accuracy trade-off, movement time changes as a function of the additional bits of information that have to be processed to achieve the task demands (Shannon & Weaver, 1949). In other words, if the rate at which information can be processed is stable then a participant must compensate for increases in difficulty by increasing and/or decreasing movement time so that the information processing required to achieve the amplitude/target can be completed.

Following extensive reformulations of the speed-accuracy trade-off (for reviews see Elliot et al., 2010; Guiard & Olafsdottir, 2011) one of the most highly respected and noted accounts of the underlying kinematic structures of this relationship was developed by Meyer et al., (1988). Taking into account not only the forward motor command, but also the online perceptual components of goal directed movements, Meyer et al., furthered Woodworth's original model by developing an explanation involving a pre-planned initial impulse movement followed by visual/proprioceptive driven discrete corrective submovements as the effector approached the target (Meyer et al., 1988). Elliot et al., (2010) advanced this model to incorporate the formation of a pre-movement motor plan paralleled with the online comparison between the anticipated and actual efferent and afferent motor/sensory information (also see Davidson & Wolpert, 2005; Harris & Wolpert, 1998; Miall & Wolpert, 1996). Indeed, cortical differences have been shown in tasks where movements are primarily externally driven by the feedback during performance compared to internally driven movements that can operate in the absence of feedback (Debaere et al., 2003). To further explain, in a condition of high accuracy demand (e.g., large A to small W) slowing of participant movement is essential to provide the opportunity for afferent-based error reduction, particularly in the visually driven online component of the movement (approaching the target). However, to completely understand the kinematic components of goal directed movement, one must first recognize that motor strategies and control processes greatly differ based upon the demands the task imposes in parallel with perceptual feedback provided.

Discrete Vs. Cyclical Control

Over the past 60 years, target directed movement investigations have traditionally been explained through two diverse theoretical perspectives: Dynamic models which characterize movements as cyclical in nature (Crossman, 1960; Fitts, 1954; Welford, 1960; Langolf et al., 1976; Turvey, 1990; Kelso, 1995; Buchanan et al., 2003, 2004, 2006) and information processing models which characterize movements as composed of discrete segments (Fitts, 1964; Schmidt et al., 1979, 1998; Meyer et al., 1982, 1988; Plamondon & Alimi, 1997). Regardless of the theory related to the composition of the movement structure, what has been repeatedly shown in speed-accuracy trade-off studies is a shift in control strategy related to the demand of the task (e.g., Buchanan et al., 2003, 2004, 2006; Mottet & Bootsma, 1999; Guiard, 1993, 1997). Utilizing a target width scaling model where ID was shifted during a trial, Buchanan and colleagues (Buchanan et al., 2004, 2006) noticed that participants transitioned from discrete to cyclical or vice versa between ID=4.0 and ID=4.9.The range between these IDs led the authors to propose $ID_c \approx 4.5$ as a critical boundary where movement variability is increased prior to transition to an alternative mode of control. Easier movements (lower IDs) in continuous Fitts' tasks are often characterized as harmonic. Kinematic analysis of these movements traditionally reveals a lack of corrections in the initial movement trajectory profile, equal proportion of time dedicated to accelerating and decelerating the limb, and minimal if any dwell time seen at target reversal. This form of control is commonly referred to as cyclical and in most cases seen at lower ID tasks. Conversely, difficult tasks (higher IDs) are typically characterized as in-harmonic. Kinematic analysis of these movements traditionally reveals adjustment to the initial movement trajectory, greater movement time utilized in the deceleration phase than acceleration phase, and increased dwell times present at target reversal. This form of control is commonly referred to as discrete in nature and in most cases seen at higher ID tasks (Buchanan et al., 2004, 2006).

For many years, studies examining speed-accuracy trade-offs have utilized traditional methods (e.g., tapping a finger, moving a peg, dragging a computer mouse, manipulating a stylus pen, etc.) without enhanced visual displays. Previous experiments have investigated the role that instruction (e.g. strategies and extended practice) play in enhancing motor performance (e.g., Boyle et al., 2012b; Guiard, 2009; Kovacs et al., 2008), with minimal to no success. (It is important to note here that for the purpose of this dissertation, improved performance will be defined as a production of faster movement time while maintaining high endpoint accuracy about the target area). In other words, many researchers have replicated the idea that speed-accuracy trade-off movements are typically not improved without some form of visual/physical manipulation (for review see Casiez et al., 2008). However, investigators today have become progressively more interested in enhancing movement performance by enhancing the visual feedback provided in virtual displays (e.g., Boyle & Shea, 2013; Boyle et al., 2012a; Fernandez & Bootsma, 2008; Kovacs et al., 2008)

For a number of years studies investigating the impact of visual displays/feedback manipulations have been predominantly seen in the human computer interfaces literature (Bohan & Scarlet, 2003; Casiez et al., 2003; Guiard, Beaudouin-Lafon, & Mottet, 1999). Researchers now are interested in looking more closely at how these manipulations change the control processes involved in producing high difficulty aiming responses. Following a two component model of control, (Davidson & Wolpert, 2005; Harris & Wolpert, 1998; Miall & Wolpert, 1996; Meyer et al., 1988; Woodworth, 1899) motor performance manipulations to movements of high difficulty are predominantly seen in one of two ways. First, visual/perceptual information can improve discrete control processes especially in terms of augmenting the performer's ability to decrease the time dedicated to making corrections. To further explain, these manipulations allow participants to produce initial ballistic movements with higher success as far as projected trajectory, which also allow participants to make fewer adjustments approaching the target area (Guiard et al., 1999). Secondly, shifts from discrete control to more cyclical control are present if perceptual manipulations are successful at alleviating task difficulty constraints (Guiard et al., 1999; Kovacs et al., 2008). Previously mentioned studies (Boyle & Shea, 2011; Buchanan et al., 2006; Guiard, 1993) have shown that lower ID movements are typically controlled using cyclical control processes while high ID movements rewire more discrete error detection and correction processes (e.g., Buchanan et al., 2004, 2006; Kovacs et al., 2008). Elements that allow performers to successfully produce high ID movements with more cyclical control could result in more proficient control.

Enhancing Goal Directed Movement

Through technological advancements it is possible to transform the information provided the performer by enlarging a virtual display of task constraints and/or performance. In traditional speed-accuracy trade-off studies, the visual and spatial coordinates of the target are isomorphic with the task constraints. In other words, the visual angle of the amplitude/width assembly scales with the movement restrictions defined by the ID. Although Fitts' (1954) original work and many experiments that followed have utilized modest movement tasks (e.g. physically tapping a stylus back and forth on a table) with only the natural visual information available, currently research has seen a resurgence in enhancing motor performance by manipulations to the perceptual information available (e.g., Bohan & Scarlet, 2003; Boyle & Shea, 2013; Casiez et al., 2008, Fernandez & Bootsma, 2008; Guiard et al., 1999, Kovacs et al., 2008).

Displaying a two-point scale of feedback information (micro and macro), Guiard et al., (1999) was successfully able to show that the motor system is extremely adaptable at making movements to targets at difficulties as high as ID=12. These small targets were reached by reducing target widths to minimal levels of presentation (in pixels) by presenting them to participants in a custom designed dual cursor feedback task. The task consisted of a cursor representing the initial projected trajectory (macro) while a second cursor represented the "homing in" on the small target (micro). The results of this study show that the perceptual/motor system is more than proficient at executing movements to high difficulty/small targets if provided the appropriate level of augmented feedback. In this study, Guiard concludes that it is not the motor command, but vision that is the limiting factor related to motor control in complex goal directed movements.

Along the same vein, a study by Kovacs et al., (2008), examined what function visual angle had in the control and execution of reciprocal movement between two high ID targets. In this experiment, physical constraints of target width and movement amplitude where kept constant, while visual depiction of the task parameters were systematically enlarged to augment visual information. Results from this study revealed that participants moved faster at an ID of 6 when the visual display of the task was enhanced (2.5x) than when the visual display was not. Although the enlarged display provided enhancement at an ID=6, the 2.5x visual display did not however, change movement performance at the lower IDs (3 and 4.5). Further analysis revealed harmonicity values surpassed scores traditionally present at high ID movements which are typically seen very low (H>.5) (Guiard, 1997; Buchanan et al., 2006). Furthermore, the amount of time devoted to the deceleration phase under the 2.5x visual presentation at ID=6 was markedly decreased compared to performance seen in the 1x visual display at ID=6. Significant decrease in dwell time and increase in percent time to peak velocity under the 2.5x visual presentation were consistent with a shift in control strategies from discrete to more cyclical. Concluding remarks from this study point to two potential reasons these enhancements were present. First, the neuromuscular system was capable of utilizing stored mechanical energy during limb reversal, leading to a more cyclical form of motion. Second, the period spent decelerating the limb was decreased considerably from the small to large display with ID = 6, with an associated increase in the percent time to peak velocity for the 2.5x display, again suggesting a shift in performance consistent with movement toward a more cyclical form of control (Buchanan et al., 2006).

In another example, a recent experiment utilizing a reciprocal Fitts task, manipulated the association between physical movement information and visual movement presentation of the cursor on the screen (non-linear gain) where the targets were presented (Fernandez & Bootsma, 2008). The manipulation provided what the authors termed a “softening-spring” effect that altered phases of the movement where large visual bursts and cursor slowing were most beneficial. The results of this study found advantages of applying a non-linear gain to the movement feedback as the difficulty of the task increased (i.e. faster movement times). Thus, altering the visual gain of the task display has the potential to influence the degree to which feedback is used to adjust the progress of the movements and ultimately enhance movement times at higher difficulty tasks.

The use of enlarged feedback presentations has not only provided some remarkable results in goal directed target movements, they have also recently been a leading issue of discussion in the study of bimanual coordination. A string of recent studies (e.g., Boyle et al., 2012c; Kovacs et al., 2010a, b) revealed that a variety of multifrequency and phase shifted, bimanual coordination tasks, traditionally thought to be extremely difficult or even impossible to efficiently produce without prolonged practice, could be successfully generated with only a few minutes of practice when Lissajous displays and templates defining the target movement pattern were provided. To further explain, Lissajous presentations allow the performance of separate effectors to be presented as a solitary point (e.g., cursor) in the display with left limb movement, for example, resulting in vertical movement of the cursor and right limb movement resulting in the horizontal movement of the cursor. When a Lissajous template is utilized, participants find it quite simple to track the outline designated by the template which results in the production of the goal bimanual coordination pattern.

It has been noted, however, with concurrent feedback displays that performers are susceptible to becoming dependent on the display information provided and are unable to effectively produce the goal movements when the display is removed. Indeed a study recently replicated that applying a non-linear gain as previously discussed (Fernandez & Bootsma, 2008) does result in enhanced motor performance compared to untransformed target movement, however, these enhancements were shown to be absent immediately following the removal of the manipulation (Boyle et al., in press). Furthermore, one cannot help but question whether the motor system is learning a new strategy in the manipulation or the enhanced movement is simply related to performing under the influence of the feedback? Debaere et al., (2003) offered validation that neuroanatomical substrate is changed when participants are performing in the absence or presence of influenced visual feedback. But again, does this change in neural activity relate to the encoding of a flexible motor program? Since there are abundant examples of participants developing a degree of dependency when simultaneous enhanced feedback is provided during acquisition (e.g., Schmidt and Wulf 1997; also see Salmoni et al., 1984), researchers have investigated methods of minimizing this dependency (e.g., Winstein et al., 1994; Winstein & Schmidt, 1990; Wulf & Schmidt, 1989).

A study by Kovacs and Shea (2011) revealed, in a bimanual coordination experiment when participants were attempting to learn a 90 phase shift with augmented Lissajous feedback, that participants were able to effectively produce the desired coordination pattern with little practice. Following the withdrawal of the feedback on the retention test; performance vastly deteriorated leading to the conclusion of a strong dependency on the augmented feedback. However, when the augmented feedback was systematically reduced, the authors found that participants could be “weaned” from their dependency on the feedback. Their results showed that participants were able to produce the complex bimanual coordination pattern with and without the augmented display if the presentation enhanced the learner's motor representation.

Studies investigating motor performance and perceptual feedback have also found that the removal of sensory information from practice to test generally results in performance detriments relative to when information is unchanged. This information could potentially be a reference used to determine when errors are made (visual feedback), vision of the limbs, or task specific parameters (i.e. difficulty, frequency, and amplitude). This perspective maintains that participants develop specific feedback processing procedures which are disrupted if the feedback is withdrawn or changed. Proteau (1995) showed that even after 200 trials of performing a specific goal directed movement, absence of the visual information representing the specific requirements of the task resulted in deteriorated performance.

In research examining goal directed movement enhancements, it is possible for movement displays to not only present targets and/or obstacles but to provide the performer with a predefined movement template. Recently, an experiment was designed that involved participants making reciprocal movements in order to follow a sine wave template (Boyle et al., 2012a). If participants were successful in tracking the sine wave template they would execute a smooth acceleration followed by a smooth deceleration approach to the target with the trajectory of the acceleration and deceleration profiles defined by amplitude and movement time dictated by the period of the sine wave. Not surprisingly, while tracking the sine wave template kinematic component analysis revealed that the participants utilized a smaller proportion of the total movement time in the deceleration phase of the movement and achieved smaller degree of variability in the movement endpoint than participants provided a typical Fitts' display. It is important to note that although movement performance was enhanced, it was not at the cost of sacrificing accuracy (hits, end point variability). Furthermore, what was even more unexpected was that when the sine wave tracking participants were transferred to a traditional Fitts target task, the participants performed the task at a level of performance that far exceeded a control group who had practiced the Fitts task throughout the entire study. The finding that the performance of the Sine group on the Fitts transfer test did not result in a performance decrease was also intriguing from a specificity of learning standpoint (e.g., Coull et al., 2001; Elliott et al., 1997; Proteau, 1995). As previously mentioned, research on this subject has found that when sensory information available during practice is removed or altered on the test trials, performance commonly declines in relation to when information presentation is unchanged. This viewpoint argues that participants acquire specific feedback processing procedures which are disturbed if the feedback is removed or altered. In the Sine condition the participants obviously utilized the sine wave template to direct their performance; however, what is unique is the level of performance they display when this source of information was removed on the Fitts transfer test. Although these findings are inconsistent with the specificity of learning hypothesis, the authors rationalized that the participants were not using the template to constantly guide their movements, but rather the template prompted them to adopt a more cyclical control. The participants utilized the sine wave template only to tune-in the correct parameters (amplitude and period) to match the wave form in the acquisition phase of the study. Therefore, removing the sine wave template did not disrupt performance because the amplitude could now be rescaled to the targets presented in the Fitts condition leaving the temporal parameter (period) open to be re-scaled.

As interesting as the findings from the sine wave enhancement were, recent reviews in current pending literature (Boyle et al., in revision) have raised questions. For example, is the "optimized" design of the sine wave a necessary feature to elicit the enhancement, or does simply tracking a sine wave template promote a flexible form of motor performance? In other words, would the same effect be expected if participants were instructed to track a sine wave that does not guide the performer through an acquisition period of harmonic/cyclical control? One potential way to investigate this question is by having participants track kinematic patterns traditionally seen in Fitts target tasks (ID = 6), but in the form of a sine wave template. This design could be made by recording the performance of a participant on a Fitts target task and displaying that displacement data as a trial-by-trial template for another participant to track during training. Yoking a participants experience to another participant (Master) stimulus exposure/response is a common technique used in Instrumental learning (Skinner, 1937; for review see Rescorla & Solomon, 1967). The benefit of this design allows the investigator to examine whether the motor response seen is a direct effect of the stimulus-response relationship. Examinations that further the understanding of the sine wave effect not only provide greater insight in to the flexible nature of the neuromuscular system, they also provide future opportunities to re-examine previous notions of natural declines in goal directed limb movement.

Aging Motor Behavior

A wealth of literature has examined the control processes associated with goal directed movement, as well as how these movement characteristics can be enhanced through augmented perceptual manipulations. Furthermore, an abundance of research has described the kinematic variables associated with aging unimanual, bimanual, fine, gross, simple and complex movements of the limbs and hands (for review see Voelcker-Rehage, 2008). In her review of aging motor performance, Voelcker-Rehage points out that as abundant as these examinations have been at explaining performance differences between specific age groups, little research has examined elderly limb movement from a *motor learning* enhancement perspective.

It has been shown that with advanced aging almost all human neural (cognitive and motor) events become reduced (Birren, 1974). A result of this decrease is that elderly people lose the ability to generate task-relevant and/or specific levels of muscle force in the context of action. This decrease has been attributed to a loss of overall muscle function and has been associated with changes in a number of mechanisms involving factors intrinsic to the muscles neural connections (Thompson, 2009). Specific muscle changes found in the elderly include reduced sensitivity (Kinoshita & Francis, 1996), increased average muscle force (Galganski et al., 1993), increased firing rate of motor units (Enoka et al., 2003), and disrupted recruitment and firing rate synchronization (Erim, 1999). Structural changes in muscle properties include atrophy of fast twitch motor units and/or switching to slow twitch units and also a decrease in the number of spinal cord alpha motor neurons (Lexell, 1993, Enoka et al., 2003). Consequences of these changes over time include an overall decline in strength due to loss of muscle cross-sectional area and muscle mass (Thompson, 2009).

In regard to learning and performance (cognitive/behavioral), elderly show decreased performance in cognitive tasks involving spatial and working memory and detriments in motor and sensorimotor control of actions (for review see Ketcham, 2002). In examining goal directed movement, elderly adults typically produce up to 70% slower movements than younger adults, and this effect is even more pronounced as task difficulty is increased

(Seidler-Dobrin & Stelmach, 1996; Ketcham, 2002). Even though elderly adults show decreased movement time, they typically do not differ statistically with younger participants on accuracy scores (Goggin & Meeuwsen, 1992). This is not surprising because kinematic analysis of elderly goal directed movement has revealed that they tend to produce movements with low peak velocity (Cooke et al., 1989) paired with longer deceleration profiles (Bellgrove et al., 1998). By definition of the speed-accuracy trade-off: if speed is decreased, accuracy will increase. Furthermore, elderly participants show increased corrective submovements as they approach a target (Ketcham, 2002). When placing emphasis on accuracy (decreasing width with constant amplitude), elderly participants show decreased movement times relative to younger participants. These decreases in movement times are heavily related to a substantial increase in secondary corrective submovements. In other words, the elderly have to make more afferent based corrections around the target compared to young participants. When placing emphasis on distance (Increasing amplitude with constant target width), elderly participants show a decrease in peak velocity profiles compared to young (Ketcham, 2002).

A study by Pratt et al., (1994) showed that although differences in goal directed corrective submovements to a target were present between elderly and young participants, both groups improved substantially related to their respective groups after extended practice. Again, younger participants outperformed the elderly, however, it is important to note that improvements over extended practice shed light on the functional plasticity of the neuromuscular system, or potentially a decrease in cortical noise. Imaging studies have shown that although motor performance decreases as we age (especially at difficult tasks), cortical activation increases with goal directed movement (Heuninckx et al., 2005). It has been hypothesized that this increase in activation represents the plasticity of the brain in the face of neurodegenerative changes related to motor control (Grady, 1994; Cabeza, 1997; Buckner, 2004). In one of his many noted works regarding motor behavior, Swinnen (2002) said, “it is not sufficient to ask how new patterns of neural excitation can be built up — we also need to ask how the pre-existing patterns can be suppressed”.

Imaging research has shown that imagined and executed movements show nearly the same cortical activation areas (Skoura et al., 2005). Neural imaging studies have shown that these include the parietal and prefrontal cortices, pre-motor and primary motor cortices, supplementary motor area, cerebellum and basil ganglia, and spinal cord. This relationship between imagined and executed pattern of activation has been shown in experiments examining movements of the hands, fingers, toes, tongue and even walking. Recently a study by Skoura et al., (2005) concluded that elderly participants did not differ from younger participants in imagined movements of the limbs in a pointing task. This result suggests that deficits seen in elderly performance may not necessarily be related to a planning issue, but rather an execution or monitoring issue.

Examining encoding strength, a study by Shea et al., (2006) tested young and elderly participants on a random and blocked multi-element sequence learning task. Results from this study concluded no difference between retention and transfer tests in young and elderly in the random sequence, leading the authors to conclude that both groups are capable of processing information similarly. However, further results concluded that young outperformed the elderly significantly in blocked acquisition and retention, leading the authors to further confirm the notion that elderly participants, although did not struggle in random, failed to recognize or develop a strategy in the blocked sequence learning.

Due to its practical applicability, it is no surprise that most studies investigating improved elderly motor performance are found in the field of human-computer interaction. Based from this field of research, traditionally investigating mouse movements, solutions have been suggested which make use of a dynamic control-display gain (Keyson, 1997), or a larger cursor activation area (Kabbash & Buxton, 1995) to promote faster performance without increasing target size. These interaction techniques have been shown to be successful in improving the performance of elderly adults in basic goal directed object-selection tasks (Worden et al., 1997). Another successful interaction technique involves dynamically expanding target size on the screen as the cursor approaches (McGuffin & Balakrishnan, 2002). This technique was found to significantly improve target selection time in younger adults (McGuffin & Balakrishnan, 2002) and in elderly adults (Bohan & Scarlett, 2003), suggesting that subjects were able to modify their initial motor response (i.e., to a small initial target) to take advantage of the final expanded target size. An investigation utilizing "sticky" icons also shows that elderly adults can produce fast and accurate movements to difficult targets (Worden et al., 1997). This process works by creating a dynamic gain that adjusts the cursor based upon the velocity of the operated tool as it approaches the target.

As beneficial as these tasks have been for improving elderly performance, as discussed previously, the manipulations listed enhance discrete forms of control which may be susceptible to feedback dependency. In other words these manipulations do not teach a new strategy of motor control, they simply support motor responses to difficult tasks by increasing speed of the initial ballistic phase of the primary movement while simultaneously alleviating problems of monitoring afferent information by increasing functional target width (also see Kovacs et al., 2008).

Finally, plasticity and functionality changes have been shown in research examining movement through a sinusoidal wave pattern smoothly with a paretic effector (finger). Carey and colleagues (2002) showed that after substantial training at index finger flexion and extension tracking a sine wave, participants with moderate motor impairment show increased cortical activation and functional movement accuracy when later tested on a transfer target task. Importantly for this manuscript, what was not as pronounced was how the comparative group (healthy elderly) performed over time on the task. Carey concluded that cortical activation and functionality did increase over time (in the healthy subjects); however, this was not as substantial as the stroke participant enhancement (which was the purpose of the study).

In summary, goal directed limb movement has repeatedly been shown to follow a speed-accuracy trade-off in relation to the constraints (A & W) of the task (Fitts, 1954; Elliot et al., 2010). A large number of studies have investigated the basic kinematic components that make up goal directed movements (Guiard, 1996) along with differences in movement structure associated with shifts in task difficulty (ID) (Buchanan et al., 2006). A variety of visual/perceptual feedback tasks have shown unique motor enhancements related to the design of the manipulation (Casiez et al., 2008) however, enhancements are most likely seen at the cost of a feedback dependency (Kovacs & Shea, 2011). Recently a study showed that tracking a template that directed the movement through a cyclical yet smooth path resulted in decreased movement time without increasing error when later tested on a speed-accuracy trade-off target task (Boyle et al., 2012a). What is still not clear, however, is the nature to the learned enhancement along with the applicability of the sine wave training effect to other populations.

CHAPTER III

EXPERIMENT I

Introduction

In many goal directed movement activities, speed is typically traded off for accuracy as the difficulty of the task is increased. For almost sixty years, discrete and reciprocal aiming tasks, often referred to as Fitts' tasks (Fitts, 1954; Fitts & Peterson, 1964), have been used to investigate the control processes governing the speed-accuracy trade-off in rapidly aimed movements. Following Shannon's information theory (1949), Fitts developed an index of difficulty (ID=log2 (2A/W)) to depict the interactive effect of target width (W) and movement amplitude (A) on movement time (MT). In Fitts' (1954) original work and in a large number of replications, one consistent finding has been that MT scales linearly with increasing ID, an ever-present relationship which has come to be respectfully known as ‘‘Fitts' Law.'' With consideration to movement across a range of IDs, studies over the past thirty years have focused on identifying kinematic markers in the aiming trajectory in an attempt to develop more sophisticated models of the MT-ID relationship. For example, aiming tasks have been used to develop models whereby corrective submovements of the limbs trajectory are linked together to insure accuracy (Crossman & Goodeve 1963; Meyer et al., 1988; Plamondon & Alimi, 1997); models in which the non-linear kinematics of the aiming trajectory change as a function of ID, with emphasis placed on clarifying differences in cyclical and discrete forms of action (Adam et al.,1996; Buchanan et al., 2003, 2004, 2006, Guiard, 1993,1997; Mottet & Bootsma, 1999; van Mourik & Beek, 2004) and performance enhancements given select feedback presentations. (Boyle & Shea, 2011; Boyle et al., 2012a; Guiard et al., 2009; Kovacs et al., 2008).

In a recent experiment using a reciprocal aiming task, Boyle et al., (2012a) provided participants a movement path which they described as "optimized" in comparison to typical trajectories seen when observed participants at movements between targets at similar movement amplitude (e.g. $A=16^o$) and target widths (e.g. $W=.5^o$). Participants were asked to follow the path, indicated by a sine wave template, by flexing and extending a lever in order to move a cursor in a manner that would track the template. If participants were successful in tracking the sine wave template they would execute a harmonic/smooth acceleration phase followed by a smooth deceleration phase. It is important to note that the period of the sine wave participants were asked to track was set to match typical movement times seen at this level of difficulty (ID = 6). Following a retention test in the respective condition (test 1), all participants were asked to perform a transfer test in which they were asked to rapidly flex and extend the cursor in and out of two defined target areas as rapidly and accurately as they could (test 2). The results from this study revealed that participants in the Sine condition not only made faster movements (decreased movement time) on the transfer (Fitts) test (Test 2) compared to participants who practiced the Fitts task during acquisition, but these movements were not acheived at the cost of kinematic variables that might have shifted to account for the speed increase. In other words, while movement time and dwell time decreased, accuracy (hits, endpoint variability) remained high and % time to peak velocity increased leading to an overall form of control characterized as more cyclical in nature.

As unique as these findings were, the sine wave tracking protocol still warrants further investigations. For example, what constitutes appropriate training in the sine wave condition? Is tracking the sine wave presented in the Boyle et al., (2012a) experiment specifically constructed to enhance movement on the transfer test, or would participants experience the same performance enhancement by simply following a modified presentation of the sign wave template? In other words, was the enhanced performance of the sine group on test 2 directly related to the stimulus-response relationship present during sine wave training? One possible way to further investigate the sine wave enhancement is to design an experiment where a new set of participants are yoked to performance seen in the original experimental design. In the study of goal directed movement or movement optimization, this technique has widely been underserved (Slifkin & Brener, 1998). From a human motor learning perspective, yoked designs have been utilized in studies investigating self-regulating knowledge of performance (KP) in sequence learning tasks (Chiviacowsky & Wulf, 2002; Hansen, Pfeifer & Patterson, 2011; Patterson & Carter, 2010) balance tasks (Hartman, 2007; Wulf & Toole, 1999) and throwing tasks (Chiviacowsky et al., 2008; Janelle et al., 1997). To further explain, a fixed control group yoked to a group that self-regulates the delivery of feedback receives feedback in the same relative and conclusive manner. The control group is yoked to the decisions the “Master” has decided without prior knowledge that this situation is even predetermined. Research has shown that traditional yoked-control groups typically do not learn the task as well as the self-regulated groups (for review see Wulf, Shea & Lewthwaite, 2010). This finding is thought to occur because individuals potentially may not receive feedback on trials for which it would be a beneficial learning experience. From this perspective with regard to movement optimization through sine wave training, participants were aware of their current performance on all trials due to the online presentation of limb displacement (i.e. the moving cursor used to track the sine wave). However, what is not clear was the nature of learning involved by experiencing the sine wave template. In other words, is it the visual experience of tracking the sine wave what elicited the movement enhancement or does the enhancement require a combination of both the optimized visual template paired with the physical representation of acting on it? Yoking one performer to the displacement profile of another performer (Master) ensures that the yoked participant physically interacts with the same kinematic patterns the “Master” experienced during their training condition (Sine or Fitts). However, this yoking design only answers half of the sine wave enhancement question. Providing a visual template of the displacement profile of the “Master” in the form of a template presentation could be used to investigate the role that visual templates play in the movement enhancement seen in Boyle et al., 2012a. If enhancements were observed for a yoked participant, who tracked the template constructed from typical Fitts task performance, which at this level of difficulty is typically characterized is in-harmonic visually driven discrete control, then previously shown enhancements following an “optimized” sine wave template would be due to the experience of tracking per se rather than the harmonic motion produced by tracking the sine template.

Therefore the purpose of Experiment I was to not only replicate the sine wave enhancement findings observed in Boyle et al., (2012a), but further investigate this enhancement by yoking a new set of participants to displacement performance seen in the Sine training and Fitts target task conditions.

Method

Participants

Participants (N=32) between the ages on 18 and 25 received class credit for participating in the experiment. The experimental protocol was approved by the IRB for human subjects’ research at Texas A&M University. Before participation, all participants read and signed approved informed consent documents. Participants were not aware of the specific purpose of the study and had no prior experience with the experimental task.

Apparatus

The apparatus consisted of a 40.64 cm lever. The lever was attached to the right side of the table and pivoted on a near frictionless rotating axis. The lever freely moved in the horizontal plane. An adjustable handle was affixed to the distal end of the lever. Adjustable positioning of the handle ensured that the elbow (arm flexion/extension) was positioned directly over the axis of rotation (*Figure 1B*).

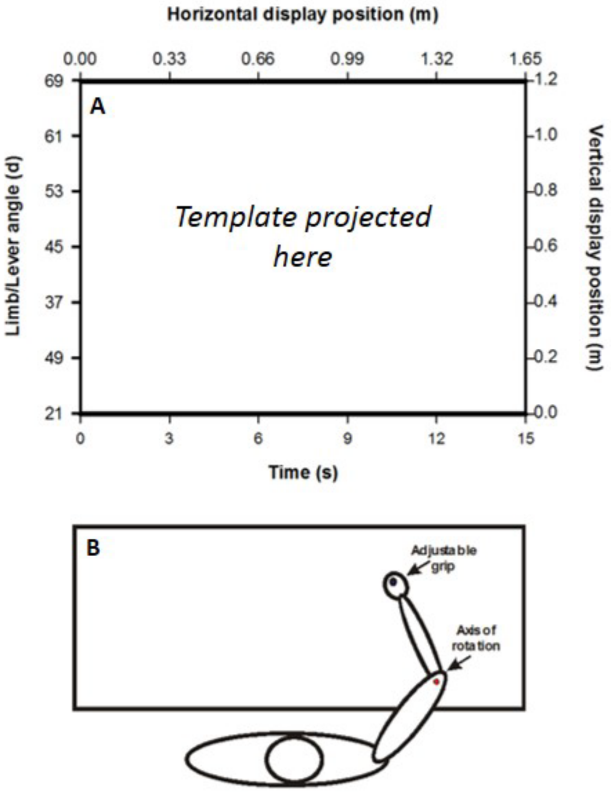

Figure 1. Dimensions and specifications of the projected image display (A). Position of the participant and manipulated apparatus (B).

A potentiometer sampling at 200 Hz was attached to the bottom of the lever. A board was placed over the limb to occlude vision of the moving effector. A mounted video projector was used to display the task (targets, sine wave and cursor). The image of the task and cursor were displayed on a wall 2m in front of the participants (*Figure 1A*). The dimensions of the displayed target measured 1.64 x 1.23 m. A height adjustable chair allowed the participants to comfortably rest their arm on the manipulated lever. The cursor and targets were generated with custom software.

Procedure

Before entering the testing area participants were randomly assigned to one of four groups (N=8 per group) that differed in terms of the practice conditions (Fitts-Master, Fitts-Yoked, Sine-Master, Sine-Yoked) (*Figure 2 A-D*).

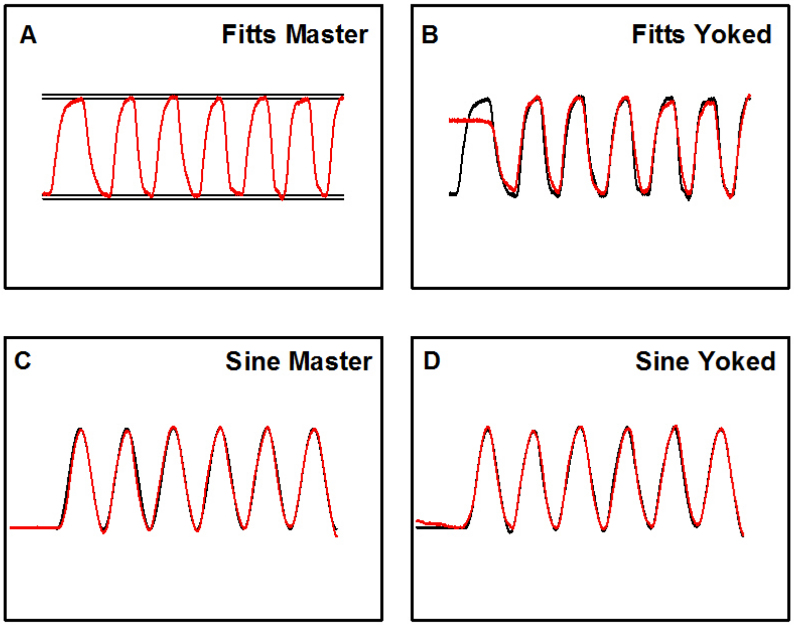

Figure 2. Illustrations of the acquisition displays for the Fitts-Master, Fitts-Yoked, Sine-Master and Sine-Yoked. Template/Target display (black) and participant performance (red).

Participants grasped the handle at the distal end of the lever. Motion of the lever was restricted to horizontal flexion/extension about the elbow. Flexion moved the lever towards the body and extension moved the lever away from the body. Movement of the lever was projected as a white cursor.

The goal of each trial in the Fitts-Master condition was to move the cursor in and out of two defined target areas by rapidly flexing and extending the lever. The projected cursor represented online knowledge of the limbs displacement and the targets were defined by two red rectangular shaped areas enhanced by a black background. Participants were told to move the cursor between the targets as fast as they could, while maintaining perfect accuracy. A constant ID = 6 ($A=16^o$, $W=.5^o$), was used in all Fitts conditions. Participants in the Fitts-Master condition performed 45 trials of acquisition at the Fitts target task, with the final trial of the acquisition period analyzed for performance (Test 1). The displacement data during each individual trial of acquisition for the Fitts-Master participants was recorded and displayed as a template for participants in the Fitts-Yoked condition to track. This custom generated template was directly linked for only a single Master-Yoked pairing and was presented during acquisition to the Fitts-Yoked participants for the same amount of trials experienced by participants in the Fitts-Master condition. Fitts-Yoked participants were simply told to track the template to the best of their ability. No other mentions of speed or accuracy were given in the instructions. Following 45 trials tracking the template created from the Fitts-Master performance, the final trial was subjected to analysis and represented the performance of Test 1 for the Fitts-Yoked participants.

The goal of each trial in the Sine-Master condition was to move the cursor up and down in order to track a displayed sine wave template. The amplitudes of the Sine wave matched that of the Fitts task (16^{o}). Following 45 trials of acquisition, the final trial was subjected to analysis and represented the participant's performance for Test 1. Similar to the Master-Yoked pairings previously discussed, the unique displacement profile of each Sine-Masters movement was recorded and displayed as the template for each yoked pairing in the Sine-Yoked condition. Following 45 trials of acquisition tracking the template created from the Sine-Masters displacement, the final trial was subjected to analysis and represented the performance values for Test 1.

Shortly after acquisition, all participants in all conditions were then asked to perform 9 trials at a Fitts target task (Test 2). All participants on Test 2 were asked to move between the targets rapidly and accurately as they could. The last trial on Test 2 was subject to analysis for all participants.

Measures and Data Analysis

Data from the potentiometer signal was used to calculate total time, movement time, dwell time, endpoint variability, peak velocity and percent time to peak velocity. Limb displacement time series was dual-passed filtered (Butterworth, 10 Hz) with data reduction performed using MATLAB. A three-point central difference algorithm was used to calculate of velocity. All dependent measures of limb movement were analyzed on a half-cycle basis. To calculate movement onset, peak velocity of a half cycle was identified and traced backwards to a value 2.5% of that peak velocity value. Movement offset was calculated by tracing forward to a value 2.5% of that movement's peak velocity before reversal to the next movement. Total time (TT), or movement time that includes dwell time was calculated by, $TT = \text{movement offset}_i - \text{movement onset}_i + \text{dwell time}_i$. Movement time (MT) was calculated by $MT = \text{movement offset}_i - \text{movement onset}_i$. Dwell time (DT) was calculated by the equation DT = movement onset_{i+1} – movement offset_i. Percent time to peak velocity (%TPV) was determined by the equation, %TPV= (PV_i - onset_i)/ (onset_i –offset_i) where PV_i is the time at which peak velocity occurs in the half cycle. To examine the continuous and discrete nature of the limb trajectory as examined by Guiard (1993) (also see Buchanan et al., 2003, 2004, 2006) an index of harmonicity (HM) was calculated centered on inflection points in the acceleration time-series. The value of HM was computed as the ratio of minimum to maximum acceleration within each half-cycle motion of the limb. Whenever the value of HM was <0 (one positive and negative inflection point), the value of HM corresponded to a value of zero. A value of HM=1 represents cyclical or complete harmonicity in the limb displacement trace, while a value of HM=0 represents the construction of discrete movement sections in the displacement trace. A value of HM=0.5 was defined here as the demarcation point between a shift from discrete to cyclical motion (Guiard 1997). Movement end-point variability (EPV) was calculated as the standard deviation of movement endpoints about their own mean.

TT, MT, DT, %TPV, PVEL, HM and EPV were analyzed in separate Condition (Sine, Fitts) x Control (Master, Yoked) x Test (Test 1, Test 2) analyses of variance (ANOVAs) with repeated measure on Test. Simple main effects analyses were utilized when appropriate as post-hoc procedures to follow up on significant main effect and interactions, respectively. An α=.05 was used for all tests.

Results

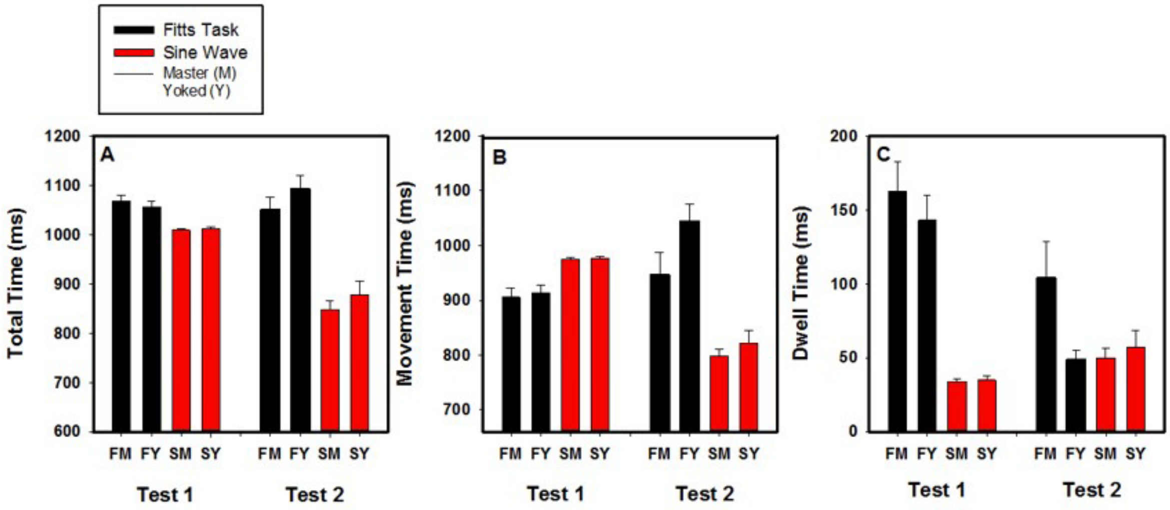

Figure 3. Mean total time (A), movement time (B) and dwell time (C) for all conditions (FM, FY, SM, SY) at Test 1 and Test 2.

Total time (TT)

The analysis indicated main effects for Condition, F(1,28)=84.67, p<.0001 and Test, F(1,28)=31.01, p<.0001. In addition the Condition x Test, F(1,28)=39.36, p<.0001 interaction was significant. Simple main effects analysis of the Condition x Test interaction indicated that TT was significantly lower for the Sine conditions (Master and Yoked) at both Test 1and Test 2 compared to the Fitts conditions. Also, the Sine conditions (Master and Yoked) produced lower TT on Test 2 compared to Test 1. No differences were seen across tests for the Fitts conditions and all other main effects and interactions failed significance.

Movement time (MT)

The analysis indicated main effects for Condition, F(1, 28)= 16.04, p<001, Control, F(1,28)= 4.80, p<.05 and Test, F(1,28)= 5.92, p<.05. In addition the Condition x Test, F(1,28)= 57.92, p<.0001 interaction was significant. Simple main effects analysis of the Condition x Test interaction indicated that MT was significantly lower for both Fitts conditions (Master and Yoked) at Test 1 compared to the Sine conditions. However, Test 2 revealed lower MT for the Sine conditions compared to the Fitts conditions. Within conditions, the Fitts condition had significantly higher MT on Test 2 compared to Test 1, while the Sine conditions had lower MT on Test 2 compared to Test 1. All other main effects and interactions failed significance.

Dwell time (DT)

The analysis indicated main effects for Condition, F(1,28)=60.66, p<.0001 and Test, F(1,28)=7.55, p<.05. In addition the Condition x Control, F(1,28)=5.24, p<.05 and Condition x Test, F(1,28)= p<.0001 were significant. Simple main effects analysis of the Condition x Test interaction indicated that DT was significantly lower for the Sine conditions on Test 1and 2 compared to the Fitts conditions. Within the Fitts condition, lower values of DT were seen on Test 2 compared to Test 1. No differences in DT were seen across tests for the Sine conditions. Simple main effects analysis of the Condition x Control interaction indicated that DT was significantly lower for both the Master and Yoked control in the Sine condition compared to Fitts. Also, within the Fitts condition, the Yoked control had significantly lower DT compared to the Master control. All other main effects and interactions failed significance

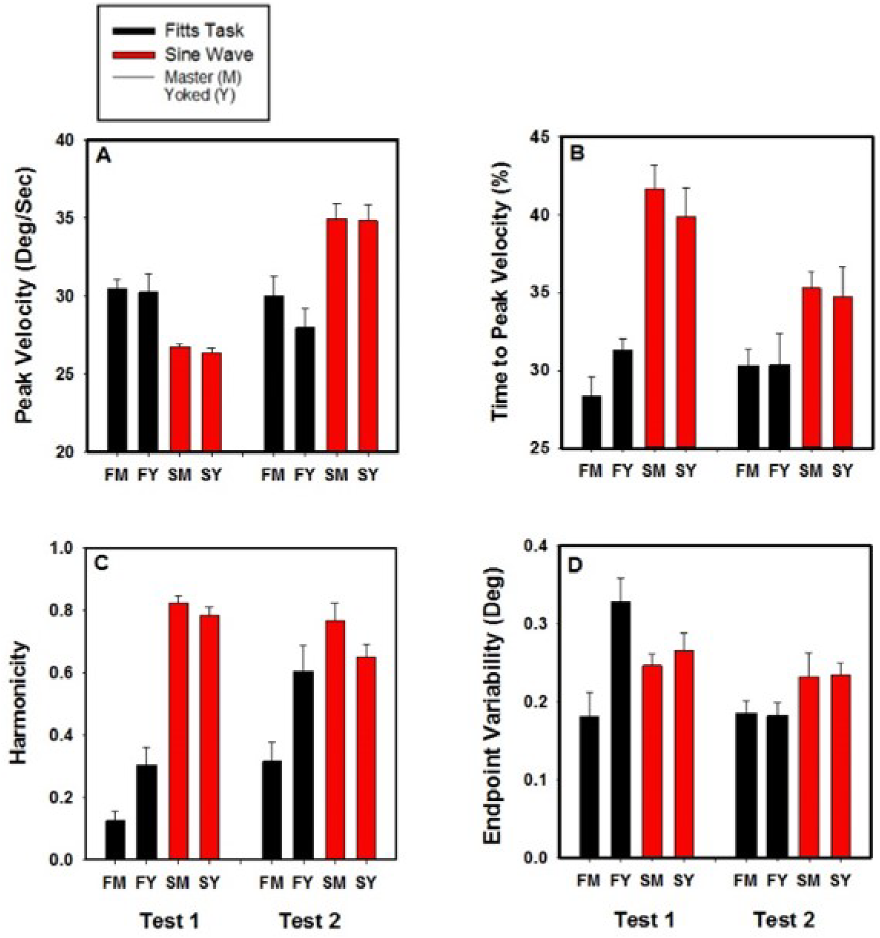

Figure 4. Mean peak velocity (A), % time to peak velocity (B), harmonicity (C) and end-point variability (D) for all conditions (FM, FY, SM, SY) at Test 1 and Test 2.

Peak velocity (PVEL)

The analysis indicated a main effect for Test, F(1,28)=26.66, p<.0001. In addition the Condition x Test, F(1,28)=52.19, p<.0001 interaction was significant. Simple main effects analysis across conditions for Test 1 indicated lower PVEL in the Sine condition compared to the Fitts condition. The analysis for Test 2 indicated lower PVEL in the Fitts condition compared to the Sine condition. Simple Main effects analysis across test determined that the

Sine condition had significantly higher PVEL on Test 2 compared to Test 1. No differences in PVEL were seen across test for the Fitts conditions. All other main effects and interactions failed significance.

Percent time to peak velocity (% TPV)

The analysis indicated main effects for Condition, F(1,28)=61.39, p<.0001 and Test (1,28)= 5.68, p<.05. In addition the Condition x Test, F(1,28)= 7.79, p<.01 interaction was significant. Simple main effects analysis of the Condition x Test interaction indicated that the Sine conditions had significantly longer %TPV compared to the Fitts conditions on both Test 1 and Test 2. The analysis also indicated longer %TPV on Test 1 for the Sine condition compared to Test 2. No differences in %TPV across test were seen in the Fitts conditions. All other main effects and interactions failed significance

Harmonicity (HM)

The analysis indicated main effects for Condition, F(1, 28)=108.96, p<.0001 and Test, F(1,28)=5.74, p<.05. In addition the Control x Condition, F(1,28)=15.27, p<.001 and Condition x Test, F(1,28)=29.39, p<.0001 interactions were significant. Simple main effects analysis of the Control x Condition indicated that the Sine Master and Yoked produced higher values of HM compared to the Fitts. Higher values of HM were also seen at Tests 1 and 2 in the Sine conditions compared to Fitts.

End-point variability (EPV)

The analysis indicated main effects for Control, F(1,28)=7.61, p<.01 and Test, F(1,28)= 6.81, p<.05. In addition the Test x Control, F(1,28)=5.2, p<.05 interaction was significant. Simple main effects analysis across control for Test 1 indicated smaller EPV in the Master than the Yoked controls. The analysis for Test 2 indicated no differences between Master and

Yoked controls. Simple Main effects analysis across test determined that the Yoked control had significantly smaller EPV on Test 2 compared to Test 1. All other main effects and interactions failed significance.

Discussion

The purpose of Experiment I was twofold. First, the experiment wanted to replicate the recent performance enhancements following sine wave tracking seen in Boyle et al., (2012a). Secondly, the experiment was designed to investigate whether tracking a template presentation of typical Fitts performance was sufficient in producing enhanced motor performance on a Fitts transfer test. Determining the degree to which the representation or control strategy developed through sine wave/template tracking practice results in a generalizable or task specific effects is important because of the potential transfer effects and training implications it provides. If tracking a template presentation of typical Fitts displacement kinematics, for example, slow movement time, long dwell time and small % time to peak velocity, results in enhanced motor performance when transferred to the Fitts target test, then the results of this study would conclude that simply tracking a non-optimized variation of the original sine wave template elicits similar enhancements. We would conclude that the mere depiction of smooth target reversal minus the visual demands of target constraints, regardless of harmonic nature, could produce motor enhancements. This would also discredit the previous claims made by Boyle et al., (2012a), that the presentation of the sine wave template used resulted in enhanced motor performance because it “optimized” the motor path the participants were asked to interact with. Statistical analysis of Experiment I replicated findings previously seen in Boyle et al., (2012a) and also leads to conclude that the sine wave enhancements observed are a direct product of the "optimized" nature of the sine waves template and not just its mere presence.

Upon completion of acquisition training (Test 1), kinematic components of sine wave tracking in both the Master and Yoked conditions revealed lower total time values compared to the Fitts conditions (Master and Yoked) (*Figure 3A*). This difference was most likely due to the increased amount of dwell time seen in both of the Fitts conditions (*Figure 3C*). It is important to note that the period of the sine wave was set to match average total times of Fitts performance previously seen in studies (e.g. Boyle et al., 2012a). Upon removal of dwell time, it is clear that the difference in total time measure was largely due to the amount of time spent slowing and reversing about the target area in the Fitts conditions. Components of movements that describe the control strategy employed revealed quite different approaches on Test 1 with regard to the condition tested. Dwell time was significantly lower in both sine wave tasks as well as a longer percent of movement time was spent accelerating the limb in comparison to the Fitts conditions. These components indicate movements were made under more cyclical or preplanned control in the sine conditions than in the Fitts (Buchanan et al., 2006). As previously seen in Boyle et al., 2012a, peak velocity values were significantly higher in the Fitts conditions compared to sine condition (*Figure 4A*). Since the target area was represented by .5 ^{o}, endpoint variability was only seen at what the author would consider an acceptable level of variability in the Fitts-Master condition. It is important to mention that out of all of the Condition x Control combinations; this was the only condition on Test 1 that presented traditional Fitts target areas. In all other conditions on Test 1 (Fitts-Yoked, Sine-Master, Sine-Yoked) participants were simply instructed to track the displayed template to the best of their ability. No mentions of accuracy constraints were ever discussed.

The analysis of performance on Test 2 suggests that participants given practice with either the sine wave conditions (Master or Yoked) developed the ability not only to effectively perform the high ID aiming task with the same movement parameters as practiced but that they also developed a strategy to rescale their movements to accommodate for faster performance. The movements produced on Test 2 for the sine groups were not only faster but also moving more towards harmonic/cyclical control (as seen in %TPV values). Even more notable was that the lower movement time for the sine groups on Test 2 was accomplished without increases in measures of accuracy (endpoint variability).

The performance of the Fitts' groups did not change from Test 1 to Test 2 with regard to total time, however; a higher value of movement time in the Fitts-Yoked group was seen from Test 1 to Test 2. This higher MT is explained by the low value of dwell time seen on Test 2 for the Fitts-Yoked participants. One possible explanation for this finding is explained by further examining the nature of the Fitts-Yoked condition. In this condition, participants (during acquisition) are still practicing tracking a template. Although the presentation does not maximize the benefit seen in the "optimized" sine training, it does still however, promote a smooth reversal through the target. This finding is interesting because in reality the Fitts-Yoked participants are not really executing a smooth reversal as seen in the longer dwell times on Test 1. They are, however, visually practicing what appears to be a smooth target reversal simply prompted by following the path of the template (even if it is Fitts displacement). This finding points to the idea that the participants are extracting some form of information from the Fitts-Yoked template, they just simply were not afforded the ideal visual/motor representation they needed to produce the desired level of performance seen in the Sine (Master and Yoked) conditions. Another interesting finding seen with the Fitts-

Yoked participants is the fact that they produce what would be considered discrete motion in the Fitts target task (Test 2). These results would appear to suggest that tracking this template actually harms motor performance even more when transferred to a self-paced Fitts target task in Test 2. It is clear that the presentation of the (Fitts) template does allow participants to extract some information from the training period. This information, although leading to lower dwell time was not sufficient in promoting a flexible form of control that allowed the performer to produce lower movement time.

Beginning with the early theories of Woodworth (1899), goal directed movements are often described as including two well-defined components; a preprogrammed initial ballistic projection of the effector toward the target followed by a second visually driven feedback stage used to make corrections to accomplish the target position (e.g., Harris & Wolpert, 1998; Keele, 1968; Meyer et al., 1982, 1988; Woodworth, 1899). Research has shown through kinematic analysis, larger engagement on the initial stage in low ID movements and greater dependency on the second stage in higher ID movements (Buchanan et al., 2003, 2004, 2006). One of the most widely cited accounts of this relationship today was developed by Meyer and colleagues (1988). Meyer's stochastic optimized submovement model describes the homing in phase, or secondary phase of the movement, as being visually guided by corrective submovements. These submovements are thought to optimally correct any deviation the initial projected limb may have encountered by making slight adjustments to the speed and trajectory, specifically around the target. However, recent studies have shown that variability in velocity during deceleration is in part related to corrective submovements; but also related to the biomechanical properties of slowing the movement in anticipation for movement reversal (e.g., Dounskaia et al., 2005; Fradet et al., 2008; Wisleder & Dounskaia

2007). By asking participants to continuously move through the target area, these submovement corrections were reduced. Similar to these findings, performance in Experiment I in both Sine conditions resulted in diminished instabilities typically observed when participants make an effort to stop in the target area. The decrease in what is typically thought of as visually driven corrective submovements was seen because tracking the template promotes cyclical/harmonic movements about the movement reversal point. This reduces some proportion of the variability typically resulting from initiating corrective movement and/or braking the movement. This idea also helps to explain the low dwell time present on Test 2 for the Fitts-Yoked participants. During their training, although they tracked movement that is considered in-harmonic, they were encouraged to move continuously through a template that guided movement reversal. It is interesting to note no differences were seen at Test 1 between the two Fitts conditions however, Test 2 results clearly show that the Fitts-Yoked participants developed a strategy that at least promoted less time spent reversing in the target. The longer %TPV for the Sine groups relative to values for the Fitts' groups is also consistent with this argument. This increase in performance for both Sine conditions on Test 2 indicated that performers did not develop a dependency on the presentation of the template, but rather tracking these "optimized" features promoted a flexible form of control that easily transferred to a goal directed target task.

In relation to the literature regarding Master-Yoked design, this experiment potentially adds a new perspective. Within motor learning, this design has traditionally been used to investigate feedback schedules related to knowledge of performance (KP) and or results (KR) (for review see Wulf, Shea & Lewthwaite, 2010). The main reason to design experiments with this construction is to further investigate the stimulus-response relationship related to a specific desired outcome and further the conclusion on if the stimulus in fact elicited the motor learning/response. This design was notably different however, than traditional designs because participants in the Master control where not instructed nor given control on any stimulus-response presentation schedule. In other words they are simply termed the Master because their displacement provides the template for the Yoked participants. Also in relation to a traditional instrumental learning perspective (Skinner, 1937), the Master participants are making a response (flex/extend the lever) to the presented stimulus (sine template/Fitts targets) however, no outcome determines any more-or-less stimulus exposure for the Yoked participants; they simply are presented with a different visual presentation of a stimulus (compared to the Fitts task).

Agreeing with previous studies, (Chiviacowsky & Wulf, 2002; Chiviacowsky et al., 2008; Hansen, Pfeifer & Patterson, 2011; Hartman, 2007; Janelle et al., 1997; Patterson & Carter, 2010; Wulf & Toole, 1999) it would appear that yoking a participant to tracking a template presentation of typical Fitts kinematics not only did not result in enhanced movement performance (lower movement time), but the values for movement time at Test 2 were actually higher than at Test 1 (acquisition training). What is unique however, is the finding that tracking the Fitts displacement templates in the Fitts-Yoked control did result in some form of movement strategy change. Although the template of Fitts performance resulted in higher movement time, this is most likely an effect seen because of the lower amount of time spent in dwell time. This low dwell time value encompasses half of the original findings presented in Boyle et al., 2012a and points to the idea that visually tracking this template is not fully understood.

CHAPTER IV

EXPERIMENT II

Introduction

Goal directed limb movement, whether discrete (Fitts & Peterson, 1964; Meyer et al., 1988) or reciprocal (Adam & Paas, 1996; Boyle & Shea, 2011; Boyle et al., 2012a; Guiard, 1997; Kovacs et al., 2008; Mottet & Bootsma, 1999) is characterized by a speed-accuracy trade-off as difficulty increases (Woodworth, 1899; Fitts, 1954). That is, as the index of difficulty (ID) increases participants must increase movement time in order to consistently "hit" the target. In terms of the kinematic variables and control processes associated with this relationship research has consistently demonstrated that as movement time decreases, percent time utilized in the acceleration phase of the movement decreases. This indicates that as difficulty increases movement control shifts from preplanned, more cyclical control to online, more discrete control (e.g., Buchanan et al., 2006).

In a recent experiment by Boyle et al., (2012a), a Fitts' group was asked to practice a typical elbow flexion/extension reciprocal Fitts' task with an amplitude (A) of 16^{o} and target width (W) of 0.5^{o} (ID=6). Participants were encouraged to move as fast and accurately as possible while maintaining a minimum of 90% hit rate. A Sine group during acquisition was asked to follow a sign wave template in the display. The template was constructed with an amplitude of 16^{o} and a period that resulted in total times comparable to that used by participants in the Fitts' group. Participants were asked to follow the path indicated by the template by flexing and extending their elbow/lever. If participants were successful at tracking the sine wave template they would execute a harmonic (smooth, symmetrical acceleration and deceleration phases) that would also reverse in the target area, even though the target lines were not present in the display. Following Test 1 in which the respective groups were tested under the conditions they experience during acquisition, both groups were asked to perform Test 2 under the Fitts' conditions. The results revealed that the Sine group not only had lowered movement times on Test 2 compared to the participants who practiced under the Fitts conditions during acquisition, but movement time was substantially reduced from Test 1 and similar to that found for the Fitts group on Test 2. In other words, while movement time and dwell time were lowered, accuracy (hits, endpoint variability) remained high and % time to peak velocity became higher leading to more harmonic motion.

As interesting as these findings were, the sine wave protocol is still not fully understood. Note that the period of the cursors movement across the sine template was set to match the total time observed in the Fitts' group. However, when the Sine group was transferred to the self-paced Fitts' task the participants moved significantly faster than they were required to move given the sine wave template and the movement time under this condition was strikingly faster than that achieved on Test 1 or Test 2 by the participants in the Fitts' group that trained under the test conditions. The fact that the Sine group altered their movement time suggests that they did not learn a time dependent control strategy but could rescale their movements when provided the opportunity. Also, the previous chapter examined if following a custom template constructed from Fitts performance would enhance movement performance. The results from that chapter concluded that following a template considered "un-optimized" does result in lower dwell time, however, no enhancements related to reduced movement time were seen. These results agree with the previous notion formed from Boyle et al., 2012a that concludes that training at an "optimized" sine template promotes a flexible form of cyclical control. The fact that the movement amplitude in Boyle et al., 2012a remained constant across tests, however, does raise the possibility that participants learn a movement strategy that is specific to that amplitude experienced. Alternatively, participants in the Sine group may learn a more generalizable control strategy that would allow them to not only scale movement time but also amplitude. If the sine wave protocol does result in a generalizable movement representation it would greatly increase the utility of this training protocol.

Therefore, the purpose of Experiment II is to determine whether enhancements related to sine wave template tracking are specific to the amplitude experienced during the exposure or more generalizable allowing amplitude to be rescaled when Fitts task conditions are required. We predict that participants who experience moving in a sine wave pattern adopt a more cyclical control strategy whereby they “tune-in” the specific amplitude/period requirements when faced with the typical Fitts task requirements.

Method

Participants

Participants (N=36) between the ages on 18 and 25 received class credit for participating in the experiment. The experimental protocol was approved by the IRB for human subjects’ research at Texas A&M University. Before participation, all participants read and signed approved informed consent documents. Participants were not aware of the specific purpose of the study and had no prior experience with the experimental task.

Apparatus

The apparatus used in Experiment II was identical to that used in Experiment I**.**

Procedure

Before entering the testing area participants were randomly assigned to one of four groups that differed in terms of the practice/training conditions (16^{o} Sine Wave, 16^{o} Fitts Task, 24^{o} Sine Wave, 24^{o} Fitts Task) (*Figure 5*), with the restriction that each group is comprised of 9 participants.

A constant ID = 6 was used in all Fitts conditions. Movements at amplitude of 16^{o} had a corresponding target width of ($.50^{o}$), while movements at amplitude of 24^{o} had a target width of ($.75\,^{o}$). The goal of each trial in the Sine condition was to move the cursor up and down in order to track the sine wave template. The amplitudes of the Sine condition matched that of the Fitts tasks (16^{o} and 24^{o}). During acquisition, the participants would only perform the task at their given amplitude and condition (Fitts or Sine). Each participant performed 4 blocks consisting of 9 consecutive 15 second practice trials. To prevent fatigue, each trial was separated by a 10 second rest interval. Upon completion of the initial practice trials a retention test of 9 trials of the practiced condition were administered (Test 1). Following completion of the retention test, a transfer test (Test 2) involved all groups performing 9 trials of a $16\,^{o}$ Fitts target task. All participants in Test 2 were asked to move between the targets rapidly and accurately. The last trial on Test 1 and Test 2 were subject to analysis.

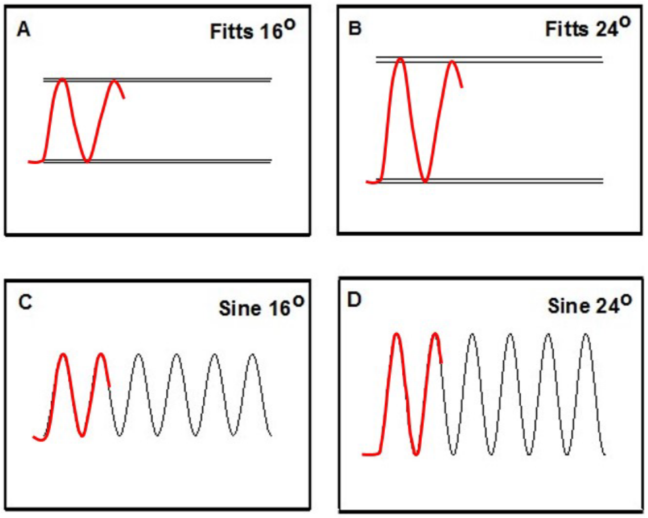

Figure 5. Illustrations of the acquisition displays for the Fitts 16^{o}, Fitts 24^{o}, Sine 16^{o} and Sine 24^{o}. Sine template / Fitts target display (black). Participant performance (red).

Measures and Data Analysis

Data Measures in Experiment II follow the same calculations as in Experiment I. TT, MT, DT, %TPV, PVEL, HM and EPV were analyzed in separate Condition (Sine, Fitts) x Amplitude (16^{o}, 24^{o}) x Test (Test 1, Test 2) analyses of variance (ANOVAs) with repeated measure on Test. Duncan's multiple range tests and simple main effects analyses were utilized when appropriate as post-hoc procedures to follow up on significant main effects and interactions, respectively. An α=.05 was used for all tests.

Results

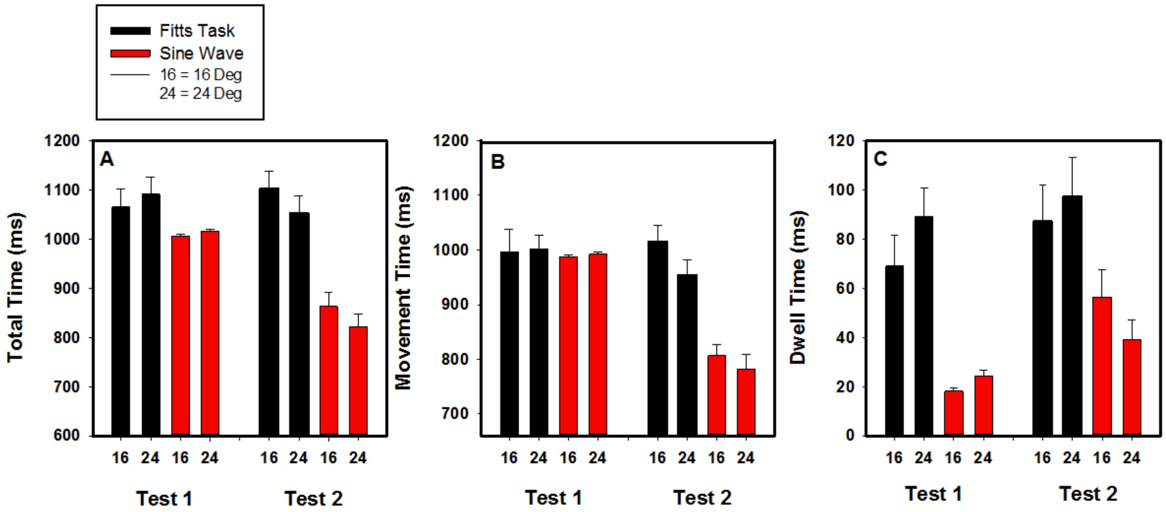

Figure 6. Mean total time (A), movement time (B) and dwell time (C) for both amplitudes (16^{o}, 24^{o}) and conditions (Fitts, Sine) at Test 1 and Test 2.

Total time (TT)

The analysis indicated main effects for Condition, *F*(1,32)=37.46, *p*<.0001 and Test, F(1,32)=29.13, p<.0001. In addition the Condition x Test F(1,32)=27.82, p<.0001 interaction was significant. Simple main effects analysis of the Condition x Test interaction indicated that TT was significantly lower for the Sine Wave group compared to the Fitts group in both Tests 1 and 2. Similarly, TT was significantly lower at Test 2 than Test 1 for the Sine Wave conditions. No differences were seen across tests for the Fitts conditions. All other main effects and interactions failed significance.

Movement time (MT)

The analysis indicated main effects for Condition, *F*(1,32)=23.58, *p*<.0001 and Test, F(1,32)=52.10, p<.0001. In addition the Condition x Test F(1,32)=38.40, p<.0001interaction was significant. Simple main effects analysis of the Condition x Test interaction indicated no difference in MT at Test 1 between conditions, however, MT was significantly lower for the Sine Wave group compared to the Fitts group at Test 2. Similarly, MT was significantly lower at Test 2 than Test 1 for the Sine Wave group. No differences were detected on Test 1 for either condition or amplitude. All other main effects and interactions failed significance.

Dwell time (DT)

The analysis indicated main effects for Condition $F(1,32)=26.55$, $p<.0001$ and Test, $F(1,32)=16.83$, $p<.001$. In addition the Condition x Amplitude $F(1,32)=4.68$, $p<.05$ interaction was significant. Simple main effects analysis of the Condition x Amplitude interaction indicated that DT was significantly lower for the Sine Wave group compared to the Fitts group at both Amplitudes (16^{o} and 24^{o}). DT was also significantly lower for the 16^{o} Fitts condition compared to the 24^{o}. No differences in DT were seen across amplitudes for the Sine conditions. All other main effects and interactions failed significance.

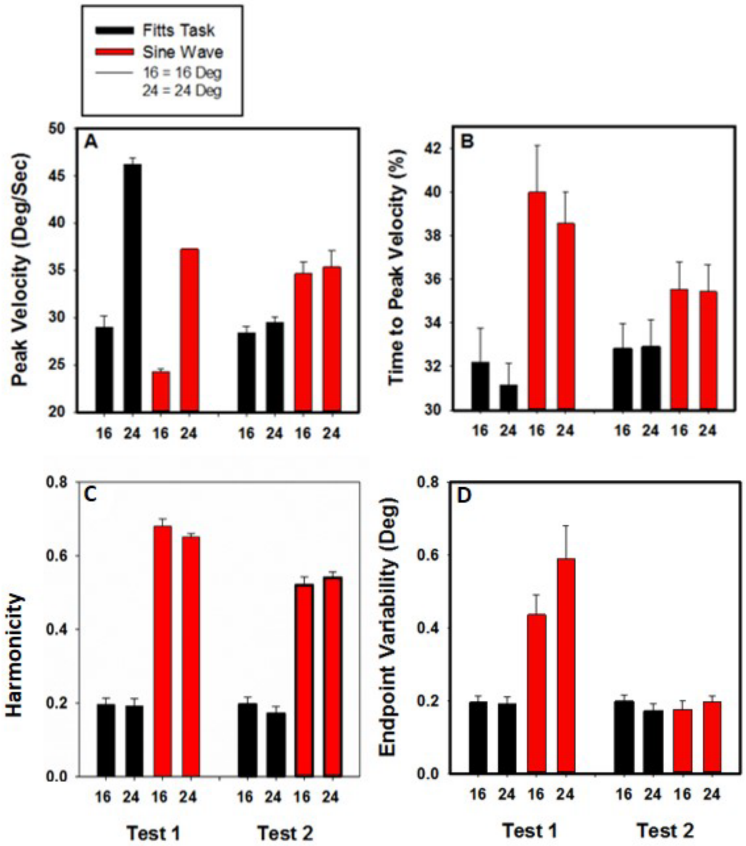

Figure 7. Peak velocity (A), % time to peak velocity (B), harmonicity (C) and end-point variability (D) for both amplitudes (16^o, 24^o) and conditions (Fitts, Sine) on Test 1 and Test 2.

Peak velocity (PVEL)

The analysis indicated main effects for Amplitude *F*(1,32)=113.83, *p*<.0001 and Test, F(1,32)=11.94, p<.01. In addition the Condition x Test F(1,32)=106.73, and Amplitude x Test F(1,32)=130.11 p<.0001 interactions were significant. Simple main effects analysis of the Condition x Test interaction indicated that PK VEL was significantly higher for the Fitts group compared to the Sine group at Test 1. However, PK VEL was significantly higher for the Sine group compared to the Fitts group at Test 2. Further condition analysis revealed that the Fitts condition significantly decreased in PK VEL from Test 1 to Test 2, while the Sine condition significantly increased in PK VEL from Test 1 to Test 2. The Amplitude x Test interaction indicated higher PK VEL values for 24^{o} amplitude compared to 16^{o} at Test 1 but no differences were detected at Test 2. The analysis also indicated PK VEL decreased significantly from Test 1 to Test 2 for $24\,^{o}$ and increased from Test 1 to Test 2 for $16\,^{o}$. All other main effects and interactions failed significance

Percent time to peak velocity (% TPV)

The analysis indicated a main effect for Condition $F(1,32)=22.16$, $p<.0001$ and a Condition x Test $F(1,32)=7.19$, $p<.05$ interaction. Simple main effects analysis of the Condition x Test interaction indicated that % TPV in the Sine Wave conditions was significantly longer in both Test 1 and Test 2 compared to the Fitts. Further analysis also revealed that %TPV was longer on Test 1 compared to Test 2 for the Sine wave condition. No differences were seen across Tests for the Fitts conditions. All other main effects and interactions failed significance

Harmonicity (HM)

The analysis indicated only a main effect of Condition, $F(1,32)=21.39$, $p<.01$, with higher HM values for the Sine groups than for the Fitts groups.

End-point variability (EPV)

The analysis indicated a main effect for Condition $F(1,32)=26.42$, $p<.001$ Test, $F(1,32)=41.32$, $p<.0001$, and Condition x Test $F(1,32)=36.13$, $p<.0001$. Simple main effects analysis of the Condition x Test interaction indicated that EPV was significantly larger for the Sine Wave conditions compared to the Fitts at Test 1 and no differences seen between either conditions at Test 2. EPV was also significantly larger for the Sine group on Test 1 compared to Test 2. No differences across Test were seen in the Fitts conditions. All other main effects and interactions failed significance

Discussion

The purpose of the following experiment was to determine if enhancements related to tracking an optimized sine template are amplitude specific. Results from Test 1 show lower values for TT movements in both Sine conditions relative to the Fitts conditions, however, upon removal of DT no differences are present at MT between the two conditions at Test 1 (*Figure 6*). Peak velocity (PVEL) was significantly higher in both 24^o conditions compared to 16^o at Test 1. According to the speed-accuracy trade-off, this finding was expected. %TPV and EPV were both longer in the Sine conditions compared to the Fitts at Test 1. These findings are also not surprising due to the smooth nature of tracking the sine template (%TPV) paired with verbal instructions that make no reference to accuracy (EPV). Following acquisition (Test 1), analysis of performance on Test 2 suggest that participants given practice with the 16^o and 24^o sign wave templates developed the ability not only to effectively perform the high ID aiming task with the same movement parameters as practiced but that they can rescale their movements to accommodate changes in amplitude. The movements produced on Test 2 for the sine groups were not only faster (lower total time and movement time) but also more cyclical (as seen in %TPV values). Furthermore, the lowered movement time for the sine groups on Test 2 was paired with a reduction in EPV from Test 1 to Test 2 (*Figure 7*).

These findings are surprising from a “specificity of learning” standpoint (Proteau, 1995). The specificity of learning hypothesis proposed that during practice the participant selects the source or sources of feedback that they feel ensure optimal performance. Thereafter, participants selectively process this information while refining their performance and ignore other sources of information provided in the display. Support for the specificity of learning can be found in experiments using a large variety of tasks (e.g. Blandin et al., 2008; Khan et al., 2002; Proteau 1995). However, this did not seem to be the case for the Sine groups. When the sine wave template was removed on Test 2 participants' total time and movement times were significantly lowered while maintaining an acceptable rate of end point variability. This suggests that they were not selectively utilizing the sine wave template to produce their movement during practice but rather it appears that the practice with the sine template resulted in them adopting a more harmonic movement control strategy whereby they learned to "tune-in" the specific amplitude and period requirements specified by the sine wave template. Thus, they did not become dependent on the template appearing in the display. This is particularly important characteristic of the protocol because participants were able to easily adapt to changes in amplitude and still exhibit the positive characteristics related to more harmonic motion.

Control theories related to aiming movements often describes movements as involving two distinct stages; an initial ballistic preprogrammed stage that projects the limb toward a target and a second "homing in" stage where visual and proprioceptive feedback are used to make adaptive corrections to achieve the target position (e.g., Harris & Wolpert 1998; Keele 1968; Meyer et al., 1982, 1988; Woodworth 1899) with greater reliance on the initial stage in low ID movements and greater reliance on the second stage in higher ID movements. Given the constraints of the task, researchers have assumed that participants optimize their control by finding a compromise between movement time and accuracy. One widely noted representation of this relationship is explained in a stochastic optimized submovement model developed by Meyer et al., (1988). Meyer and colleagues proposed that aimed movements are comprised of a primary submovement followed by optimized corrective submovements. These submovements are thought to optimally correct any deviation the initial projected limb may have encountered by making slight adjustments to the speed and trajectory, specifically around the target. Dounskaia and colleagues (e.g., Dounskaia et al., 2005; Fradet et al., 2008; Wisleder & Dounskaia 2007), however, investigated similar velocity profiles that are traditionally observed in the online deceleration phase of high ID movements. They conclude that variability in velocity during deceleration is in part related to corrective submovements; however, non-corrective submovements the movement are also present during deceleration phase of the movement. Dounskaia et al., (2005) proposed that these submovements are more associated with stopping the movement than actually making corrections. The authors demonstrated this by asking participants to move through the target instead of stopping on the target. This resulted in a reduction in the submovements typically observed. Similarly, in the present experiment performance in the Sine condition resulted in reduced fluctuations often observed when participants attempt to stop in the target because the sine protocol promoted cyclical movements around the reversal point. In other words, by asking participants to practice moving in a cyclical way (by following the sine wave) the practices promotes smooth movement through the target. This reduces some proportion of the variability typically resulting from initiating corrective movement and/or braking the movement. The longer %TPV for the Sine groups relative to the values for the Fitts' groups is consistent with this argument. The increase from discrete to a more cyclical form of control for the Sine condition on Test 2, where the sine template was removed, indicated that participants were not dependent on the template but rather these features promoted a strategy that was effective even when they were removed.

Early work in motor learning describes the basic motor program as program that can be used to govern the production of a wide range of actions from within specific movement classes (Schmidt, 1975; Schmidt, 1988). According to Schmidt, the motor program is an abstract representation of movement output that centrally organizes and controls the various degrees of freedom involved in performing a movement (Schmidt and Lee, 2005). It has been suggested that efferent and afferent signal pathways allow the central nervous system to anticipate, plan or guide these movements (Schmidt and Lee, 2005). Necessary to this program is the need for relative timing, force and sequence elements. In the case of the present experiment, the training during acquisition is set to match the time traditionally present at a Fitts target task of ID = 6, while the forces and sequencing of the movement production do not change drastically from trial to trial. Evidence of a flexible form in control is seen when the participants begin to move faster when they are transferred to a target task (Test 2) that affords them the opportunity to self-pace their movements between the targets. From this perspective it is not that surprising that the sine wave training, no matter the amplitude trained at, is more than capable of producing fast yet accurate cyclical movements to target difficulty that traditionally results in slower more discrete control.

CHAPTER V

EXPERIMENT III

Introduction

Goal directed limb movement between targets has repeatedly been shown to follow a linear speed-accuracy trade-off as difficulty of the task increases (Woodworth, 1899; Fitts, 1954). This relationship has been shown in experiments involving continuous (Adam & Paas, 1996; Boyle & Shea, 2011; Boyle et al., 2012a; Guiard, 1997; Kovacs et al., 2008; Mottet & Bootsma, 1999) and discrete movements of the limbs (Fitts & Peterson, 1964; Meyer et al., 1988). In terms of the kinematic variables and control processes associated with this relationship, research has reliably demonstrated that as movement time decreases, the percentage of time utilized in the acceleration phase of the limb projection toward the target decreases. This decrease in acceleration indicates that as the task becomes more difficult, movement control shifts from preplanned cyclical control to more online or discrete visually driven control (e.g., Buchanan et al., 2006). Due to technological advancements, recently studies have investigated potential ways to manipulate these shifts in control based on augmented feedback provided during difficult tasks (for review see Casiez et al., 2008)

Performance manipulations to movements of high difficulty are mainly investigated in one of two ways. First, augmented visual/perceptual displays can enhance control processes thought of as discrete in nature, particularly in terms of increasing the performer's ability to reduce the time devoted in the correction phase of the movement. Enhancements like these have typically been seen in experiments that enhance the visual information about the target area, allowing performers to spend less time monitoring accuracy in the target (Boyle & Shea, 2013; Casiez et al., 2008, Fernandez & Bootsma, 2008; Guiard et al., 1999, Kovacs et al., 2008). Secondly, shifts from discrete control to more cyclical control are present if perceptual manipulations are successful at alleviating task difficulty constraints (Fernandez & Bootsma, 2008; Kovacs et al., 2009). As previously mentioned, lower difficulty movements are typically guided by cyclical control processes while high difficulty movements are regulated by more discrete visual error detection and correction processes (Buchanan et al., 2004, 2006;). Conditions that allow performers to successfully produce high ID movements with more cyclical control could result in more efficient and skillful control.

As successful as these methods have been at enhancing motor performance, it has been shown that performers under the influence of concurrent feedback displays are susceptible to becoming dependent on the manipulation provided. To further explain, removal of the feedback results in immediate deterioration of enhanced performance previously seen. For example, a recent study by Boyle et al., (in press) replicated the performance improvements recently shown in Fernandez & Bootsma's 2008 study by applying a non-linear gain in a Fitts target task. Although it was not the main focus of the study, the authors noticed that upon removing the feedback, performance enhancements observed while under the influence of the non-linear gain immediately deteriorated (Boyle et al., in press). Understanding issues related to perceptual enhancements are not only important from a practical standpoint, especially as we age, but questioning how they impact the motor systems ability to re-learn or develop new forms of movement strategy are equally as important of an investigation.

According to US news world reports, there are now more Americans age 65 and older than at any other time in U.S. history (65 million in 2010 census). With this rise in a growing demographic, research has focused on a number of ways to alleviate issues of daily activity related to aging. Theories related to information-processing capacities is presently thought as the source of slowing of cognitive and motor behaviors throughout aging (Bashore et al., 1997; Birren, 1974; Cerella, 1985; Salthouse, 1985, 1988; Welford et al., 1969). With regard to movement of the limbs, studies have frequently shown that increasing the difficulty of a goal directed target task results in a greater increase in movement time in elderly adults compared to young (Welford et al., 1969; Seidler & Stelmach, 1998; Ketcham et al., 2002; Rey-Robert et al., 2012). Following a two component model of goal directed movement, these deficits in performance have been shown in initial limb projections (i.e. low values of peak velocity) (Bellgrove et al., 1998; Brown, 1996; Cooke et al., 1989; Goggin & Meeuwsen, 1992; Pratt et al., 1994) and also in secondary correction phases (i.e. limb deceleration profiles) (Darling, Cooke, & Brown, 1989; Ketcham et al., 2002). With regard to secondary phase corrections, elderly adult performers show a significantly larger number of corrective submovements near the target area compared to young adult (Darling et al., 1989; Seidler-Dobrin & Stelmach, 1998; Walker et al., 1997). From a kinematic analysis perspective, it would be safe to suggest that elderly people tend to operate more from a discrete or visually driven form of control compared to young. Although natural shifts in this form of control have been repeatedly shown to change based on the ID (Buchanan et al., 2003, 2004, 2006), it would appear from the literature that elderly participants potentially would have an even greater time making a shift from visually driven discrete control to preplanned cyclical control. Procedures allowing improvements from this slower form of error monitoring control to faster preprogramed control could potentially provide a new platform to further the understanding of the our motor systems capabilities as we age.

Although previously described age differences are present in natural environments, improvements in motor performance with regard to aging have been shown in human-computer interaction studies. Goal directed elderly motor performance enhancements have been seen when researchers make use of larger cursor activation areas (Kabbash & Buxton, 1995; Keyson, 1997; Worden et al., 1997). Alleviating visual monitoring corrective submovements, this form of manipulation increases the saliency of the visual information about the target allowing the elderly performer to spend less time monitoring the secondary phase of the movement. Similarly, another effective technique involves a dynamically expanding target as the cursor approaches (McGuffin & Balakrishnan, 2002). This technique was found to significantly enhance target performance not only in younger adults (McGuffin & Balakrishnan, 2002) but also in elderly adults as well (Bohan & Scarlett, 2003).

With the previously mentioned studies it is clear that manipulations do exist to alleviate the highly replicated issues of motor control related to goal directed limb movement. However, as previously noted goal directed movement enhancements have also been shown to present a level of dependency to the augmented feedback provided during the task. The question then becomes, do the few listed manipulations truly improve goal directed movement of the limbs in the elderly, or are they a product of the manipulation exposure? Another way to look at this is to question whether the motor system has developed a new strategy based upon this training. As helpful as these tasks have been for improving elderly performance, all manipulations listed enhance discrete forms of control which may be highly susceptible to feedback dependency. As mentioned previously, these manipulations do not lead to a new control strategy of motor control, they simply support motor responses to difficult tasks by increasing speed of the initial ballistic phase of the primary movement while simultaneously alleviating problems of monitoring afferent information by increasing functional target width (also see Kovacs et al., 2008).

As repeatedly shown throughout this manuscript, tracking an optimized sine wave template leads to enhanced goal directed limb movement in college age participants. This manipulation has been shown to lower movement times while also preserving kinematic variables associated with accuracy and control (i.e. % time to peak velocity, dwell time, end point variability, etc.). Furthermore is the finding that these participants develop this movement strategy while practicing at varying levels of amplitude and at a template that produces a slower frequency than when asked to perform on self-paced test trials.

Based on the previous hypothesized findings, Experiment III investigates the sine wave tracking effect using elderly adults. A wealth of literature has shown that elderly people are much slower (higher movement times) at goal directed limb movements compared to young, and this deficit in movement patterns are typically seen in a slower initial ballistic phase projection of the limb followed by an increase in corrective submovements as they approach the target. Results from the previously mentioned experiments (Boyle et al., 2012a, Boyle & Shea, in press) optimized goal (sine wave) condition; we see enhancements in both of these kinematic variables. Therefore, the purpose of Experiment III is to examine if training at an optimized sine wave template aids goal directed motor behavior in the elderly. If so, what kinematic markers are most enhanced in this learning effect?

Method

Participants

Participants (N=14) between the ages of 18 - 25 received class credit for participating in the experiment (7 participants per condition). Participants (N=14) between the ages of 65 -

90 (mean age =74) received a gift card valued at $10.00 US dollars for their participation (7 participants per condition). The experimental protocol was approved by the IRB for human subjects' research at Texas A&M University. All participants in the 65 – 90 age range were screened for any neurological impairments that might hinder the study (mini-mental state exam and health questionnaire). Participants were not aware of the specific purpose of the study and had no prior experience with the experimental task.

Apparatus

The apparatus used in Experiment III was identical to that used in Experiments I and II**.**

Procedure

Before entering the testing area participants were assigned to one of two groups that differed in terms of age (Young: 18-30, Elderly: 65 - 90). The two age groups were then randomly split into two more groups that represented the condition they would train under (Fitts, Sine Wave).

Since this study aim is to investigate if sine wave training enhances movement performance in the elderly it is important to have a reference point as to where performance variables are, without inferring based on previous research findings. To design this scenario, all participants were first tested on a 9 trial Fitts task (pre-test). The final trial was analyzed and used as performance data representing Test 1. Following the pre-test, participants (all ages) were trained in their respective conditions (Sine, Fitts) for 45 trials. The final trial during acquisition was recorded and used for Test 2 values. Upon completion of acquisition, all participants were then tested on a 9 trial Fitts task post-test, Test 3. The last trial of Test 3 was recorded and analyzed as performance data.

Measures and Data Analysis

Data measures in Experiment III use the same calculations as in Experiment I and II. TT, MT, DT, %TPV, PVEL, HM and EPV were analyzed in separate Condition (Sine, Fitts) x Age (Elderly, Young) x Test (Test 1, Test 2, Test 3) analyses of variance (ANOVAs) with repeated measure on Test. Simple main effects analyses were utilized when appropriate as post-hoc procedures to follow up on significant main effect and interactions, respectively. An α=.05 was used for all tests.

Results

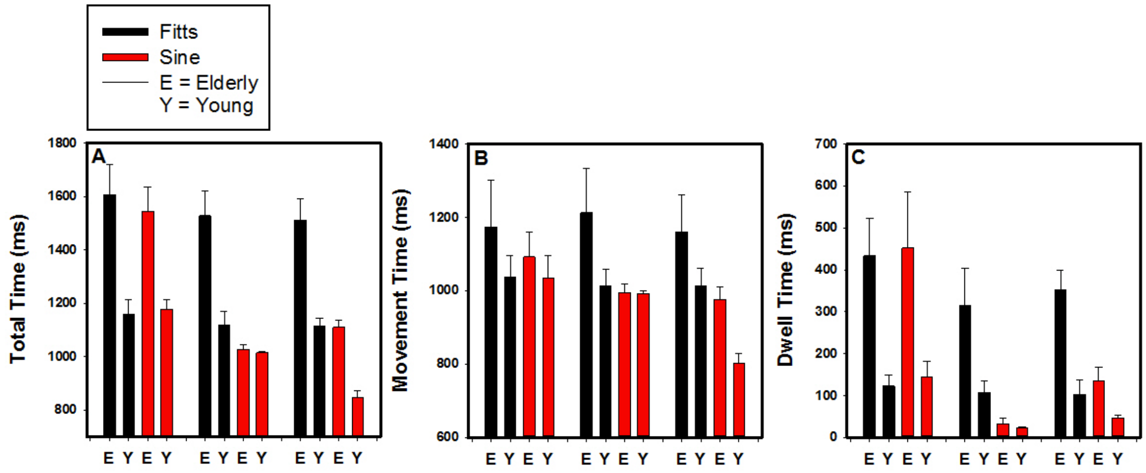

Figure 8. Mean total time (A), movement time (B) and dwell time (C) for both ages Elderly (E) and Young (Y) and conditions (Fitts, Sine) at Test 1, Test 2 and Test 3.

Total time (TT)

The analysis indicated main effects for Condition, F(1,25)=17.09, p<.001, Age, F(1, 25)= 35.47, p< .0001, and Test, F(2,47)=47.15, p<.0001. In addition the Condition x Test, F(2, 47)=22.63, p<.0001, Age x Test, F(2, 47)=7.61, p<.01 and Age x Condition x Test, F(2, 47)=5.43, p<.01, interactions were significant. Simple main effects analysis for the Age x Condition x Test interaction indicated lower TT in both Sine and Fitts conditions in young compared to elderly at Test 1. No differences in TT were seen between conditions (Fitts, Sine) in their respective age group (elderly, young) at Test 1. Lower TT was seen in both Sine age groups (elderly, young) followed by Fitts (young) and lastly Fitts (elderly) at Test 2. No differences were seen between the sine groups (elderly, young) at Test 2, however, significantly lower TT was seen in the Fitts condition for the young compared to the elderly. At Test 3, TT was significantly lower in the Sine young condition followed by Sine elderly and Fitts young together and lastly Fitts elderly. No differences were seen in the comparison sine elderly and Fitts young at Test 3. All other main effects and interactions failed significance.

Movement time (MT)

The analysis indicated a main effect for Test, F(2,47)=6.31, p<.01. In addition the Condition x Test, F(2,47)=3.91, p<.05, interaction was significant. Simple main effects analysis across Condition x Test revealed no difference between conditions at Test 1, however, lower MT values were seen at Test 2 and Test 3 for the Sine condition compared to the Fitts. Analysis within condition revealed a significant decrease in MT from Test 2 to Test 3 for the Sine wave condition. No differences were seen in the Fitts conditions across all tests. All other main effects and interactions failed significance.

Dwell time (DT)

The analysis indicated main effects for Condition F(1,25)=5.22, p<.05, Age, F(1,25)= 20, p<.0001 and Test, F(2,47)=14.27, p<.0001. In addition the Condition x Test, F(2,47)=5.17, p<.01, and Age x Test, F(2,47)=4.88, p<.05 interactions were significant.

Simple main effects analysis across Condition x Test indicated no difference between conditions Fitts or Sine at Test 1 however, lower DT values were seen in the Sine condition at Test 2 and Test 3 compared to Fitts condition. Analysis within condition revealed no differences between Fitts across tests. Lowest values of DT seen at Test 2 followed by Test 3, then Test 1, were seen in the Sine condition. Simple main effects analysis across Age x Test indicated no difference between ages at Test 1 however, lower DT was seen at Test 2 and Test 3 for young compared to elderly participants. Analysis within age revealed lowest DT at Test 2, followed by Test 3 and then Test 1 for both ages (Elderly, Young). All other main effects and interactions failed significance.

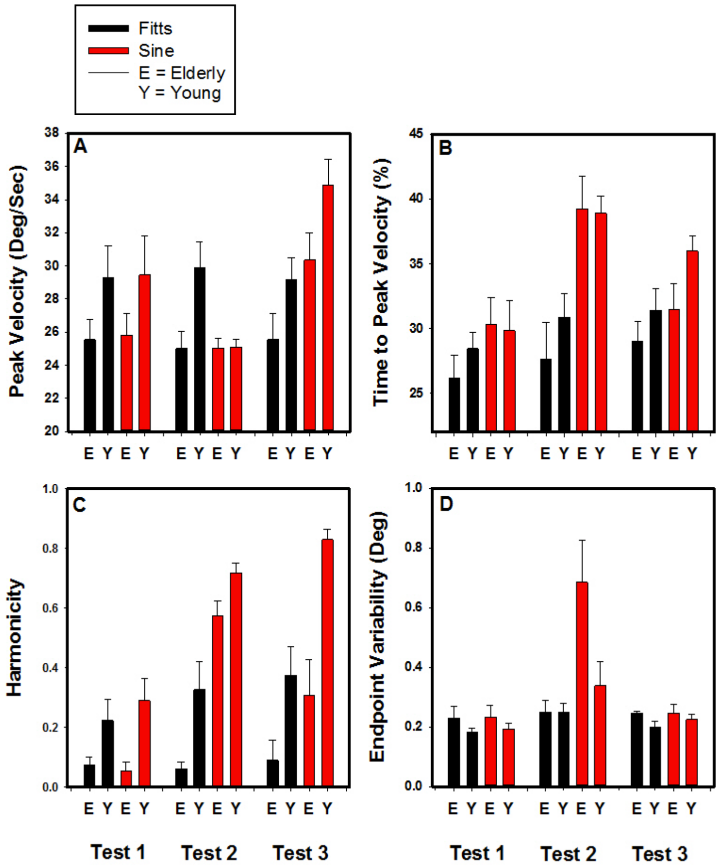

Figure 9. Peak velocity (A), % time to peak velocity (B), harmonicity (C) and end-point variability (D) for both ages (Elderly, Young) and conditions (Fitts, Sine) at Test 1, Test 2 and Test 3.

Peak velocity (PVEL)

The analysis indicated main effects for Age F(1,25)=10.06, p<.01 and Test, F(2, 47)=10.87, p<.0001. In addition the Condition x Test F(2,47)=11.51, p<.0001interaction was significant. Simple main effects analysis of the Condition x Test interaction indicated no differences in condition at Test 1, higher PK VEL values in the Fitts condition compared to Sine at Test 2 and higher PK VEL values for the Sine condition compared to Fitts were seen in Test 3. Analysis within condition revealed significantly higher PK VEL values at Test 3 compared to Test 1 and Test 2 in the Sine condition. No differences were seen across tests for the Fitts conditions. All other main effects and interactions failed significance.

Percent time to peak velocity (% TPV)

The analysis indicated main effects for Condition F(1,25)=15.04, p<.001 and Test, F(2,47)=11.28, p<.0001. In addition the Condition x Test F(2,47)=5.56, p<.01 interaction. Simple main effects analysis of the Condition x Test interaction indicated only a significant difference between conditions at Test 2, with the Sine condition having longer % TPV. Analysis within condition indicated the longest %TPV at Test 2, followed by Test 3, then Test 1 in the Sine condition. All other main effects and interactions failed significance.

Harmonicity (HM)

The analysis indicated main effects for Condition, F(1, 24)=38.22, p<.0001, Age, F(1,24)=37.04, p<.0001 and Test, F(2,48)=21.14, p<.0001. In addition the Condition x Test, F(2,48)=12.44, p<.0001 and Age x Test, F(2,48)=29.39, p<.05 interactions were significant. Simple main effects analysis of the Condition x Test interaction indicated higher values of HM in the Sine conditions compared to Fitts at Tests 2 and 3. No differences were seen between conditions at Test 1. Simple main effects analysis across the Age X Test interaction indicated higher values of HM for young compared to elderly at all Tests.

End-point variability (EPV)

The analysis indicated main effect for Conditions F(1,25)=5.10, p<.05 and Test, F(2,47)=15.31, p<.0001. In addition the Condition x Test, F(2,47)=9.78, p<.001 and Condition x Test x Age, F(2,47)=4.88, p<.05 interactions were significant. Simple main effects analysis of the Condition x Test x Age interaction indicated the largest EPV values for age elderly in the Sine condition at Test 2, with age young in condition Sine having larger EPV values compared to both age groups in condition Fitts on Test 2. All other main effects and interactions failed significance.

Discussion

The purpose of the following experiment was to determine if training with an "optimized" sine wave template would result in enhanced motor performance previously seen in Boyle et al., (2012a) in an active aging population. Research regarding the neuromuscular processes related to aging and motor control has traditionally pointed to elderly participants displaying longer movement times compared to young, with these movement kinematics displaying highly predictable patters (Ketcham et al., 2002). The results of this study are unique in that they conclude that not only are elderly participants able to enhance motor performance after sine wave training in relation to a within age comparison but these participants also show no statistical difference as far as movement time or accuracy when compared to college aged participants who have trained at the Fitts task for over 60 trials (*Figure 8*). It is also important to note here that the sine tracking participants in the elderly age group have only been exposed to the Fitts task for 18 trials (in comparison to the 60+ seen in the young Fitts group).

Results from Experiment III show that not only do elderly participants show enhanced motor performance on a Fitts target task following sine wave training with respect to a comparison across age, they also show that the neuromuscular capabilities throughout aging potentially have the ability to perform a goal directed target task relative to the performance seen by college aged participants. Interestingly, although the results from this study show enhanced motor performance in the elderly group following sine wave training, with levels comparable to young, the control or motor strategy that brings them to those kinematic values is not necessarily the same. For example, sine wave trained elderly participants on Test 3 perform the task with low values for %TPV (*Figure 9*), leading to the conclusion that they were unable to develop a smooth form of cyclical control strategy hypothesized in the previous 2 experiments as well as others regarding optimized transfer following sine wave training (Boyle et al., 2012a).

Research has shown that elderly participants react to fluctuations in task difficulty by making different modifications in response to amplitude and accuracy constraints. In the following experiment an unusual combination of kinematic markers are present in the elderly participant’s performance following sine wave tracking on Test 3 (Fitts post-test). Although a large reduction in movement time from Test 1 to Test 3 is present in the sine wave elderly group, typical control strategies pointing to a new form of adopted control are not quite as clear as seen in the young participants. For example, in the beginning stages of the movement, the performance (elderly sine wave) suggests a more preplanned mode of control is adopted by higher values of peak velocity. In other words, the initial projection of the limb has significantly increased in relation to values present on Test 1 (Fitts pre-test). However, peak velocity was reached significantly sooner than would normally be expected following sine training, indicating the elderly participants are slowing in anticipation of movement reversal. Although the elderly participants did spend a longer amount of time slowing in anticipation of movement reversal, the actual amount of time spent in the target was not significantly different compared to young participants. These findings suggest that elderly adults, although responding to the sine wave training with significant motor enhancements, are still unable to effectively propel their limb to the target in a harmonic manner. The precise cause for having a diminished ability to project the limb to a target in a fast yet harmonic manner are still not fully understood.

One potential explanation of this performance deficit could be suggested through a study that concluded that elderly adults show considerably more muscle cocontraction during goal directed target movements compared to young adults (Seidler-Dobrin & Stelmach, 1998). Research has shown that elderly adults produce normal agonist muscle bursts during movement initiation (hence the enhancement to peak velocity following sine wave training), but irregular phasic antagonist muscle activation is present throughout the deceleration phase of the movement (Darling et al., 1989). Interestingly however, this irregular muscle activation would also suggest a large amount of time spent in corrective submovements around the target as well, which was not the case in the current study.

Studies have also suggested that aging motor control involves a central planning deficit (Amrhein et al., 1991; Goggin & Meeuwsen, 1992; Haaland, Harrington, & Grice, 1993; Seidler-Dobrin & Stelmach, 1998; Stelmach et al., 1988; Welford, 1984). If this were the case however, one might expect that all task conditions would show similar deficiencies, which was not collectively the circumstance in this study. A large improvement was seen in movement times followed by lower dwell times through target reversal. A study by Walker and colleagues (1997) concluded that when accuracy constraints are removed, elderly participants exhibit peak movement velocities similar to those of the young adults. Similar to this study, when participants track the sine wave template, no mention of accuracy is given. Repeated exposure to smooth reversals about a small target area not only allows the participants to visually become comfortable with the task constraints, it allows the motor system to tune in a flexible form of control that is not normally present in a Fitts target task. In other words, tracking the sine wave allows participants to preplan the limbs projection while less attention is devoted to the accuracy constraints of the target allowing the participants to exhibit a smooth reversal (in both age groups).

CHAPTER VI

GENERAL DISCUSSION AND CONCLUSION

The purpose of Experiment I was to replicate the results seen in Boyle et al., (2012a) and determine if tracking a template of Fitts target task performance kinematics would enhance motor performance when transferred to a traditional Fitts target task (Test 2). Participants were trained in one of four acquisition conditions (Fitts-Master, Fitts-Yoked, Sine-Master, and Sine-Yoked). In the Fitts-Master condition, participants were asked to move a cursor in and out of two defined target areas as fast yet accurately as possible. Upon completion of 45 acquisition trials in the Fitts target condition (Test 1) a template for all Fitts-Master participants was generated from the recorded limb displacement data on each trial. These custom 45 trials made up the templates for all participants in the Fitts-Yoked condition. In the Sine-Master condition, participants were instructed to track a sine wave template. Following the same presentation for the Fitts-Yoked participants, the Sine-Master displacement during acquisition was recorded to custom create the template for the Sine-Yoked participants. Following acquisition trials (Test 1), all participants were asked to perform 9 trials of the Fitts target task (Test 2). Results of Experiment I replicated the results seen in Boyle et al., (2012a) by showing lower movement times in both Sine Wave groups (Master and Yoked) on Test 2 compared to both Fitts groups (Master and Yoked). That is, movement time, time to peak velocity, and endpoint variability were similar for the two sine groups indicating not only faster but more cyclical motion than for the Fitts group that practiced under the Fitts conditions the entire time and the yoked group that tracked the performance of participants in the in the Master Fitts group.

The purpose of Experiment II was to determine if sine wave tracking with a different amplitude from that used on the test will result in equally effective transfer to a Fitts target task previously seen in Boyle et al., 2012a. Participants were trained in one of four acquisition conditions where they either tracked a sine wave template with an amplitude of 16^{o} or 24^{o} (ID=6) or practiced under Fitts target task conditions with an amplitude of 16^{o} or 24^{o} (ID=6). Following 45 acquisition trials and Test 1 under the same condition as experience during practice, all participants were tested under a Fitts target task conditions with ID=6 and amplitude=16^{o} (Test 2). Results demonstrated that participants who practice with sine wave templates of 16^{o} and 24^{o} were equally effective in performing the 16^{o} Fitts task (Test 2). Movement time, time to peak velocity, and endpoint variability were similar for the two sine groups (16^{o} and 24^{o}) indicating not only faster but more cyclical motion than for the Fitts groups that practiced under the Fitts conditions the entire time.

The purpose of Experiment III was to investigate if sine wave tracking in an active elderly population would result in enhanced motor performance when later transferred to a Fitts target task. Elderly and young participants (Elderly, Young) were assigned to one of two acquisition conditions where they either practiced tracking a sine wave template or a Fitts target condition with ID=6. To establish a baseline of performance, all participants first completed 9 trials at a Fitts target task pre-test (Test1). Following 45 acquisition trials in their respective training conditions (Sine or Fitts, Test 2), all participants were tested on a Fitts target task post-test for 9 trials (Test 3). The findings of Test 1 demonstrated no differences in measure of movement time and accuracy between conditions (Sine, Fitts) for their respective age (Elderly, Young). However, Young participants displayed superior scores on all measures compared to Elderly. Results of Test 2, where participants were tested in their respective training conditions, demonstrated faster movement times for both Young groups and Elderly sine wave training compared to Elderly Fitts performance. Finally, Test 3 revealed enhanced motor performance in the Young and Elderly participants who tracked the sine wave with the Young Sine wave training displaying the fastest movement times on the Fitts target test, followed by the Elderly Sine wave and Young Fitts participants having no difference in movement time between the two and the Elderly Fitts participants resulting in the slowest times of performance.

Theoretical Considerations

Established and recent models of speed-accuracy trade-offs demonstrate goal directed movements including two distinct stages; an initial ballistic preprogrammed stage that projects the limb toward a target followed by a second “homing in” stage where visual and proprioceptive feedback are used to make subtle corrections to achieve the target location (e.g., Beggs & Howarth, 1970; Buchanan et al., 2003, 2004, 2006, Crossman & Goodeve, 1963; Guiard, 1993, 1997, Harris & Wolpert, 1998; Keele, 1968; Meyer et al., 1982, 1988; Woodworth, 1899). A highly noted account of this relationship is depicted in a model developed by Meyer et al., (1988) which refers to a stochastic optimized sub-movement. Advancing the seminal work of Woodworth (1899), Meyer et al., suggests that goal directed movements are comprised of a ballistic phase (primary sub movement) followed by homing in on target (optimized corrective sub-movements). These sub-movements are thought to optimally correct any divergence the initial projected effector may have faced by making minor adjustments to the speed and trajectory, specifically about the target area.

Further examining corrective submovements, Dounskaia and colleagues (e.g., Dounskaia et al., 2005; Fradet et al., 2008; Wisleder & Dounskaia, 2007) recently examined similar velocity profiles that are usually present in the visually driven deceleration phase of high ID movements. They suggest that variability in velocity during deceleration is indeed related to corrective submovements; however, they point out that it is important to note that non-corrective submovements are also present during movement termination. Dounskaia et al., suggests that these submovements are more coupled with stopping the movement than actually making corrections. In other words, the corrective submovements can be thought of as ‘‘fluctuations emerging from mechanical and neural sources of motion variability’’. The authors showed this by having participants instead of stopping on a target, they were asked to move through the target, ultimately minimizing the submovements typically seen. Similarly, in Experiments 1-3, performance in the optimized Sine conditions (Master and Yoked Sine from Experiment I, 16^o and 24^o Sine in Experiment II, Sine tracking for both ages in Experiment III) resulted in decreased fluctuations often present when performers attempt to stop/or in the case of reciprocal studies reverse in the target, because movements through this presentation promote cyclical/harmonic movements around the reversal point. In other words, the display characteristics promoted smooth movement through the target area. This decreases a proportion of the variability typically resulting from initiating corrective sub-movements and/or stopping the movement.

Manipulations designed to alleviate common movement tendencies have been widely investigated in unimanual and bimanual settings. Recently Boyle et al., 2012c (also see Kovacs et al., 2010a,b) demonstrated that a variety of multi-frequency and phase shifted coordination tasks could be effectively produced with limited exposure of practice when Lissajous displays and template illustrating the goal movement pattern were provided. These movement patterns were recently thought to be extremely difficult or even impossible to produce without extensive training; however, participants in this study were able to effectively produce the required bimanual coordination pattern in a matter of minutes. Lissajous displays allow the movement of two limbs to be depicted as a single point (e.g., cursor) in the display with right limb movement, for example, resulting in the horizontal movement of the cursor and left limb movement resulting in vertical movement of the cursor. Research examining bimanual coordination has shown that when exposed to lissajous display, participants find it quite easy to follow the pattern indicated by the template, which results in the production of the goal bimanual coordination pattern.

When salient concurrent feedback is provided, especially at high ID movements, participants are better able to effectively manage both the initial preprogrammed control and the adaptive corrective processes. An experiment by Kovacs et al., (2008) demonstrated a decrease in movement time and endpoint variability at ID = 6 when the size of the projected visual display was increased. This manipulation can be thought of as facilitating the secondary “homing in” phase, ultimately leaving the participants more space to tune in the correct trajectory and reversal point with lower attentional resources utilized. Alternatively, when feedback is withheld or minimized, the corrective phase of aimed movements at high IDs are often less effective due to the increase in attentional resources operators use to process visual and proprioceptive demands (e.g., Kovacs et al., 2008). It is also important to note that when the feedback manipulation is present, this enhancement was only seen at an ID = 6. By utilizing a nonlinear transformation of the task space in the display, which allowed the target area to be enlarged relative to the amplitude, Fernandez and Bootsma (2008) also found enhanced movement time for IDs between 4 and 6.

Debaere et al., (2003) provided evidence that the neuroanatomical substrate differs when participants perform with and without the presence of augmented visual feedback. This is consistent with the dependency on augmented feedback that has been shown in a number of experiments (e.g., Schmidt & Wulf, 1997; also see Salmoni et al., 1984), and also examined in ways of alleviating it (Winstein et al., 1994; Winstein & Schmidt, 1990; Wulf & Schmidt, 1989). Kovacs and Shea (2011), for example, found that participants were able to effectively perform a 1:1 with 90^o phase bimanual coordination task with augmented Lissajous feedback following only 4 min of practice. However, when feedback was withdrawn on a retention test, performance greatly declined indicating a nearly complete dependency on the feedback (Kovacs & Shea, 2011). Clearly the participants were dependent on the display to perform this difficult coordination pattern.

In the literature dependencies on concurrent feedback appear particularly strong although there are numerous examples of dependency on terminal information. The specificity of practice hypothesis proposed that during practice the participant determines the source or sources of feedback that will ensure optimal performance. Thereafter, participants selectively process this information while refining their performance and begin to ignore other sources of information provided in the display or learning environment. Support for the specificity of learning can be found in experiments using a large variety of tasks (e.g., Blandin et al., 2008; Khan et al., 2002, Proteau, 2005). Many of these experiments demonstrate the beneficial effects of information in the display while it is available, but also the detrimental effect when the information is withdrawn.

Do to the relatively new way the sine wave tracking is utilized in this experiment, a large number of future investigations are available. With relation to Experiment I, the results showed that although no improvements related to movement speed (lower movement time) were seen after tracking a sine wave template of Fitts performance, a change in the kinematic structure was present. The significant decrease in dwell time from Test 1 to Test 2 for the Fitts-Yoked participants concludes that tracking a sine wave, even if not “optimized” as previously mentioned in Boyle et al., 2012a, still provides a template that allows the participant to extract some form of information that promotes a faster target reversal. In this condition, the participant visually witnesses a template, while simultaneously moving through the physical space of movement kinematics that would be classified as discrete in nature. Making a comparison of the physical and visual nature of this condition, a logical investigation to further this idea would then allow a participant to visually witness the “optimized” template tracking procedure without the act of physically interacting with the template. So far we have seen that visual/physical exposure to an “optimized” design of the sine wave template enhances motor performance when later transferred to a Fitts target task. Visual/physical exposure to an “un-optimized” sine wave template does not promote movement speed enhancement however, does result in decreased dwell time. The question then becomes, would the visual observation of an “optimized” sine wave template bridge this gap, or does the participant need the combination of visual along with physical interaction of cyclical movement in order to develop the flexible form of cyclical control seen at Test 2?

With relation to Experiment II, future investigations should examine differing forms of sine wave templates in order to investigate the key elements of the structure of the movement related to Test 2 movement enhancement. One potential way to investigate this idea would be to provide a segmented sine wave display that matches either the initial ballistic phase of the movement (a linearly increasing line) or the smooth target reversal (a U shape at target reversal). Studies have shown that motor enhancements can potentially be related to the specific feedback manipulation present (Bohan et al., 2010). The movement enhancements, although usually concluded in movement time values, can be constructed from specific changes in distinct areas related to the composition of the movement structure. A design of this nature would highlight if a particular area of the sine wave template (initial limb projection or movement reversal) provided more necessary information related to the motor enhancement seen at Test 2.

With relation to Experiment III, future investigations should examine not only developing sine wave templates that result in lower movement time, yet harmonic motor performance in the elderly, but investigate how motor performance following sine wave training correlates with active lifestyle differences. The sine wave template in Experiment III was set to match the same period of Fitts target task performance times seen in the young participants. One possible explanation for the improved speed in the elderly participants following tracking the sine wave is the speed at which the participants were trained. In other words, would we expect the elderly participants to show lower movement time on Test 2 following training at a sine wave template that matched typical period (time) values seen for elderly Fitts performance? Also, if young participants are trained at this time would the benefit be removed on them as well? In relation to the elderly participants recruited, the participants recruited for Experiment III had self-reports of aerobic physical activity for at least three days weekly. Studies have shown that physical activity levels are directly related to neuromuscular control throughout aging (Lord & Castell, 1994) and the benefits of physical activity have been seen in balance, strength, reaction time, and flexibility to name a few (Lord & Castell, 1994, Rikli & Edwards, 1991, Spirduso, 1975, 1980, Spirduso & Clifford, 1978). Studies providing a direct comparison to the flexibility of the neuromuscular system throughout aging related to physical activity level add to the large amount of literature describing exercise as medicine throughout the lifespan.

In conclusion, tracking an “optimized” sine wave template has been shown to enhance motor performance when transferred to a self-paced Fitts target task. The benefits have been seen through a variety of presentations and age ranges. It is clear that much more work needs to be done to fully understand the training effect, but furthering the understanding of this protocol not only has the potential to provide new recommendations to the way interfaces guide and/or train motor commands, it also provides an alternative way to re-examine the flexibility of a once thought constrained motor system.

Summary

Three experiments were conducted, aimed at providing further understanding of how previously identified perceptual factors interact in influencing performance on a goal directed target task. In summary; providing participants with a sine wave tracking task does alter motor behavior when later transferred to a Fitts target task. What is interesting though is the relationship of the transfer performance seen on the Fitts task with the nature of the sine wave trained at. The results of Experiment I replicate the findings seen in Boyle et al., (2012a) by suggesting that tracking an optimized sine wave not only promotes enhanced motor performance following training, but these enhancements are also not seen at the cost of measures of accuracy. A new finding presented from this study suggests that transfer performance seen following training of a stereotypical Fitts displacement depiction in sine wave form does surprisingly promote lower dwell time about the target reversal, but this single enhancement was seen at the cost of higher MT and lower %TPV, indicating a slower more in-harmonic strategy had been formed on Test 2. To further this experiment, future studies could investigate the role observation plays in extracting important information regarding sine wave training versus Fitts target task performance. Experiment II was intended to determine whether enhancements related to the sine wave practice are specific to the amplitude experienced during the sine wave practice or more generalizable allowing amplitude to be rescaled. Results from Experiment II conclude, again, that training at an optimized sine wave, even if the amplitude differs, promotes fast yet accurate motor performance when transferred to a Fitts target task. The purpose of Experiment III was to extend the sine wave training experiment in to an aging perspective and examine if training at an optimized sine wave task promotes enhanced motor performance in an active aging population. Results from this study interestingly conclude that not only can elderly participants enhance their motor performance drastically compared to parallel age participants in a Fitts only group, but they perform the Fitts transfer test with similar movement time seen in college aged Fitts acquisition participants.

REFERENCES

Adam, J. J., & Paas F. G. W. C. (1996). Dwell time in reciprocal aiming task. *Human Movement Science*, *15*, 1-24.

Amrhein, P. C., Stelmach, G. E., & Goggin, N. L. (1991). Age differences in the maintenance and restructuring of movement preparation. *Psychology and Aging, 6*, 451-456.

Bashore, T. R., Ridderinkhof, K. R., & van der Molen, M. W. (1997). The decline of cognitive processing speed in old age. *Current Directions in Psychological Science*, *6*, 163-169.

Beggs, W. D. A., & Howarth, C. I. (1970). Movement control in a repetitive motor task. *Nature*, *225*, 722-753.

Bellgrove, M. A., Phillips, J. G., Bradshaw, J. L., & Gallucci, R. M. (1998). Response (re-) programming in aging: A kinematic analysis. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *53*, M222-M227.

Birren, J. E. (1974). Translations in gerontology: From lab to life: Psychophysiology and speed of response. *American Psychologist*, *29*, 808-815.

Blandin, Y., Toussaint, L., & Shea, C. H. (2008). Specificity of practice: Interaction between concurrent sensory information and terminal feedback. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*, 994-1000.

Bohan, M., & Scarlett, D. (2003). Can expanding targets make object selection easier for older adults. *Software Usability Research Lab at Wichita State University Usability News*, *5*.

Bohan, M., McConnell, D. S., Chaparro, A., & Thompson, S. G. (2010). The effects of visual magnification and physical movement scale on the manipulation of a tool with indirect vision. *Journal of Experimental Psychology: Applied*, *16*, 33.

Boyle, J. B., & Shea, C. H. (2011). Wrist and arm movements of varying difficulties. *Acta Psychologica*, *137*, 382-396.

Boyle, J. B., Kennedy, D., & Shea, C. H. (2012a). Optimizing the control of high ID single degree of freedom movements: Re-thinking the obvious. *Experimental Brain Research*, *223*, 377-387.

Boyle, J. B., Panzer, S., Wright, D., & Shea, C. H. (2012b). Extended practice of reciprocal wrist and arm movements of varying difficulties. *Acta Psychologica*, *140*, 142-153.

Boyle, J. B., Panzer, S., & Shea, C. H. (2012c). Increasingly complex bimanual multi-frequency coordination patterns are equally easy to perform with on-line relative velocity feedback. *Experimental Brain Research*, *216*, 515-525.

Boyle, J. B., & Shea, C. H. (2013). Micro-movements of varying difficulties: Wrist and arm movements. *Experimental Brain Research*, *229*, 61-73.

Boyle, J. B., Panzer, S., Wang, C., Kennedy, D., & Shea, C. H. (in press). Optimizing the control of high ID single degree of freedom movements: Re-thinking the power of the visual display. *Experimental Brain Research*.

Boyle, J. B., Kennedy, D., Wang, C., & Shea, C. H. (in revision). The sine wave protocol: Decreasing movement time without increasing errors. *Journal of Motor Behavior*.

Brown, A. S. (1996). Control of simple arm movements in the elderly. In A.M. Fernandez & N. Teasdale (Eds.), *Changes in sensory motor behavior in aging*. North Holland, The Netherlands: Elsevier Science, 27-52.

Buchanan, J. J., Park, J-H., Ryu, Y. U., & Shea, C. H. (2003). Discrete and cyclical units of action in a mixed target pair aiming task. *Experimental Brain Research*, *150*, 473-489.

Buchanan, J. J., Park, J-H, & Shea, C. H. (2004). Systematic scaling of target width: dynamics, planning, and feedback. *Neuroscience Letters, 367*, 317-322.

Buchanan, J. J., Park, J-H, & Shea, C. H. (2006). Target width scaling in a repetitive aiming task: Switching between cyclical and discrete units of action. *Experimental Brain Research, 175*, 710-725.

Buckner, R. L. (2004). Memory and executive function in aging and AD: multiple factors that cause decline and reserve factors that compensate. *Neuron*, *44*, 195-208.

Cabeza, R., Anderson, N. D., Locantore, J. K., & McIntosh, A. R. (2002). Aging gracefully: compensatory brain activity in high-performing older adults. *Neuroimage*, *17*, 1394-1402.

Carey, J. R., Kimberley, T. J., Lewis, S. M., Auerbach, E. J., Dorsey, L., Rundquist, P., & Ugurbil, K. (2002). Analysis of fMRI and finger tracking training in subjects with chronic stroke. *Brain*, *125*, 773-788.

Casiez, G., Vogel, D., Balakrishnan, R., & Cockburn, A. (2008). The impact of control-display gain on user performance in pointing tasks. *Human Computer Interaction*, *23*, 215-250.

Cerella, J. (1985). Information processing rates in the elderly. *Psychological Bulletin*, *98*, 67.

Chiviacowsky, S., & Wulf, G. (2005). Self-controlled feedback is effective if it is based on the learner's performance. *Research Quarterly for Exercise and Sport*, *76*, 42-48.

Chiviacowsky, S., Wulf, G., de Medeiros, F. L., Kaefer, A., & Tani, G. (2008). Learning benefits of self-controlled knowledge of results in 10-year-old children. *Research Quarterly for Exercise and Sport*, *79*, 405-410.

Cooke, J. D., Brown, S. H., & Cunningham, D. A. (1989). Kinematics of arm movements in elderly humans. *Neurobiology of Aging*, *10*, 159-165.

Coull, J., Tremblay, L., & Elliott, D. (2001). Examining the specificity of practice hypothesis: is learning modality specific? *Research Quarterly for Exercise and Sport*, *72*, 345-354.

Crossman, E. R. F. W. (1956). A theory of the acquisition of speed skill. *Ergonomics*, *2*, 153-166.

Crossman E. R. F. W. (1960). The information capacity of the human motor system in pursuit tracking. *Quarterly Journal of Experimental Psychology*, *12*, 1-16.

Crossman E. R. F. W., & Goodeve P. J. (1963). Feedback control of hand movement and Fitts' law. *Quarterly Journal of Experimental Psychology*, *35A*, 251-278.

Darling, W. G., Cooke, J. D., & Brown, S. H. (1989). Control of simple arm movements in elderly humans. *Neurobiology of Aging*, *10*, 149-157.

Davidson, P. R., & Wolpert, D. M. (2005). Widespread access to predictive models in the motor system: A short review. *Journal of Neural Engineering*, *2*, S313-S319.

Debaere, F., Wenderoth, N., Sunaert, S., Van Hecke, P., & Swinnen, S. P. (2003). Internal vs external generation of movements: differential neural pathways involved in bimanual coordination performed in the presence or absence of augmented visual feedback. *Neuroimage*, *19*, 764-776.

Dounskaia, N., Wisleder, D., & Johnson, T. (2005). Influence of biomechanical factors on substructure of pointing movements. *Experimental Brain Research, 164*, 505-516.

Elliott, D., Lyons, J., & Dyson, K. (1997). Rescaling an acquired discrete aiming movement: Specific or general motor learning? *Human Movement Science, 16*, 81-96.

Elliott, D., Hansen, S., Grierson, L. E. M., Lyons, J., Bennett, S. J., & Hayes, S. J. (2010). Goal directed aiming: Two components but multiple processes. *Psychological Bulletin, 136*, 1023-1044.

Erim, Z., Beg, M. F., Burke, D. T., & de Luca, C. J. (1999). Effects of aging on motor-unit control properties. *Journal of Neurophysiology*, *82*, 2081-2091.

Enoka, R. M., Christou, E. A., Hunter, S. K., Kornatz, K. W., Semmler, J. G., Taylor, A. M., & Tracy, B. L. (2003). Mechanisms that contribute to differences in motor performance between young and old adults. *Journal of Electromyography and Kinesiology*, *13*, 1-12.

Fernandez, L., & Bootsma, R. J. (2008). Non-linear gaining in precision aiming: Making Fitts’ task a bit easier. *Acta Psychologica*, *129*, 217-227.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, *47*, 381-391.

Fitts, P. M. (1964). Perceptual-motor skills learning. In A.W. Melton (Ed.), *Categories of Human Learning* (pp. 243-285). New York: Academic Press.

Fitts, P. M., & Peterson, J. R. (1964). Information capacity of discrete motor responses. *Journal of Experimental Psychology*, *67*, 103-112.

Fradet, L., Lee, G., & Dounskaia, N. (2008). Origins of submovements during pointing movements. *Acta Psychologica*, *129*, 91-100.

Galganski, M. E., Fuglevand, A. J., & Enoka, R. M. (1993). Reduced control of motor output in a human hand muscle of elderly subjects during submaximal contractions. *Journal of Neurophysiology*, *69*, 2108-2115.

Goggin, N. L., & Meeuwsen, H. J. (1992). Age-related differences in the control of spatial aiming movements. *Research Quarterly for Exercise and Sport*, *63*, 366-366.

Grady, C. L., Maisog, J. M., Horwitz, B., Ungerleider, L. G., Mentis, M. J., Salerno, J. A. & Haxby, J. V. (1994). Age-related changes in cortical blood flow activation during visual processing of faces and location. *The Journal of Neuroscience*, *14*, 1450-1462.

Guiard, Y. (1993). On Fitts's and Hooke's laws: simple harmonic movement in upper-limb cyclical aiming. *Acta Psychologica*, *82*, 139-159.

Guiard, Y. (1997). Fitts' law in the discrete vs. cyclical paradigm. *Human Movement Science*, *16*, 97-131.

Guiard, Y., Beaudouin-Lafon, M., & Mottet, D. (1999). Navigation as multiscale pointing: extending Fitts' model to very high precision tasks. *In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* ACM, 450-457.

Guiard, Y. (2009). The problem of consistency in the design of Fitts' law experiments: Consider either target distance and width or movement form and scale. *In: Proceedings of the 27th International Conference on Human Factors in Computing Systems*. ACM. 1809-1818.

Guiard, Y., & Olafsdottir, H. B. (2011). On the measurement of movement difficulty in the standard approach to Fitts' law. *PLoS ONE*, *6*, e24389.

Haaland, K. Y., Harrington, D. L., & Grice, J. W. (1993). Effects of aging on planning and implementing arm movements. *Psychology and Aging*, *8*, 617.

Hansen, S., Pfeiffer, J., & Patterson, J. T. (2011). Self-control of feedback during motor learning: accounting for the absolute amount of feedback using a yoked group with self-control over feedback. *Journal of Motor Behavior*, *43*, 113-119.

Harris, C. M., & Wolpert, D. M. (1998). Signal-dependent noise determines motor planning. *Nature*, *394*, 780-784.

Hartman, J. M. (2007). Self-controlled use of a perceived physical assistance device during a balancing task 1. *Perceptual and Motor Skills*, *104*, 1005-1016.

Heuninckx, S., Wenderoth, N., Debaere, F., Peeters, R., & Swinnen, S. P. (2005). Neural basis of aging: the penetration of cognition into action control. *The Journal of Neuroscience*, *25*, 6787-6796.

Janelle, C. M., Barba, D. A., Frehlich, S. G., Tennant, L. K., & Cauraugh, J. H. (1997). Maximizing performance feedback effectiveness through videotape replay and a self-controlled learning environment. *Research Quarterly for Exercise and Sport*, *68*, 269-279.

Kabbash, P., & Buxton, W. A. (1995). The “prince” technique: Fitts' law and selection using area cursors. *In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 273-279.

Kinoshita, H., & Francis, P. R. (1996). A comparison of prehension force control in young and elderly individuals. *European Journal of Applied Physiology and Occupational Physiology*, *74*, 450-460.

Keele, S. W. (1968). Movement control in skilled motor performance. *Psychological Bulletin*, *70*, 387.

Kelso, J. A. S. (1995). Dynamic patterns: The self-organization of brain and behavior. Cambridge MA: MIT Press.

Ketcham, C. J., Seidler, R. D., Van Gemmert, A. W., & Stelmach, G. E. (2002). Age-related kinematic differences as influenced by task difficulty, target size, and movement amplitude. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *57*, 54-64.

Keyson, D. V. (1997). Dynamic cursor gain and tactual feedback in the capture of cursor movements. *Ergonomics, 40*, 1287-1298.

Khan, M., Elliott, D., Coull, J., Chua, R., & Lyons, J. (2002). Optimal control strategies under different feedback schedules: Kinematic evidence. *Journal of Motor Behavior*, *34*, 45-57.

Kovacs, A. J., Buchanan, J. J., & Shea, C. H. (2008). Perceptual influences on Fitts' law. *Experimental Brain Research*, *190*, 99-103.

Kovacs, A. J., Buchanan, J. J., & Shea, C. H. (2010a) Perceptual and attentional influences on continuous 2:1 and 3:2 multi-frequency bimanual coordination. *Journal of Experimental Psychology: Human Perception & Performance*, *36*, 936-954.

Kovacs, A. J., Buchanan, J. J., & Shea, C. H. (2010b) Impossible is nothing: 5:3 and 4:3 multi-frequency bimanual coordination. *Experimental Brain Research*, *201*, 249-259.

Kovacs, A. J., & Shea, C. H. (2011). The learning of 90° continuous relative phase with and without Lissajous feedback: External and internally generated bimanual coordination. *Acta Psychologica*, *136*, 311-320.

Langolf, G. D., Chaffin, D. B., & Foulke, J. A. (1976). An investigation of Fitts' law using a wide range of movement amplitudes. *Journal of Motor Behavior*, *8*, 113-128.

Lexell, J. (1993). Ageing and human muscle: observations from Sweden. *Canadian Journal of Applied Physiology*, *18*, 2-18.

MacKenzie, I. S. (1989) A note on the information-theoretical basis for Fitts' law. *Journal of Motor Behavior*, *21*, 323-330.

Maill, R. C., & Wolpert, D. M. (1996). Forward models for physiological motor control. *Neural Networks*, *9*, 1265-1279.

McGuffin, M., & Balakrishnan, R. (2002, April). Acquisition of expanding targets. *In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems: Changing Our World, Changing Ourselves*. ACM. 57-64.

Mottet, D., & Bootsma, R. J. (1999). The dynamics of goal-directed rhythmical aiming. *Biological Cybernetics*, *80*, 235-245.

Meyer, D. E., Smith, J. E. K., & Wright, C. E. (1982). Models for the speed and accuracy of aimed movements. *Psychological Review*, *89*, 449-482.

Meyer, D. E., Abrams, R. A., Kornblum, S., Wright, C. E., & Smith, J. E. (1988). Optimality in human motor performance: Ideal control rapid aimed movements. *Psychological Review*, *93*, 340-370.

Patterson, J. T., & Carter, M. (2010). Learner regulated knowledge of results during the acquisition of multiple timing goals. *Human Movement Science*, *29*, 214-227.

Plamondon, R., & Alimi, A. M. (1997). Speed/accuracy trade-offs in target-directed movements. *Behavioral Brain Science, 20*, 279-349.

Pratt, J., Chasteen, A. L., & Abrams, R. A. (1994). Rapid aimed limb movements: age differences and practice effects in component submovements. *Psychology and Aging*, *9*, 325.

Proteau, L. (1995). Sensory integration in the learning of an aiming task. *Canadian Journal of Experimental Psychology*, *49*, 113-120.

Rescorla, R. A., & Solomon, R. L., (1967). Two-process learning theory: Relationships between Pavlovian conditioning and instrumental learning. *Psychological Review*, *74*, 151.

Rey-Robert, B., Temprado, J. J., Lemaire, P., & Berton, E. (2011). Combining movement kinematics, efficiency functions, and Brinley plots to study age-related slowing of sensorimotor processes: insights from Fitts' task. *Gerontology*, *58*, 171-180.

Rikli, R. E., & Edwards, D. J. (1991). Effects of a three-year exercise program on motor function and cognitive processing speed in older women. *Research Quarterly for Exercise and Sport*, *62*, 61-67.

Salmoni, A. W., Schmidt, R. A., & Walter, C. B. (1984). Knowledge of results and motor learning: A review and critical reappraisal. *Psychological Bulletin*, *95*, 355-386.

Salthouse, T. A. (1985). A theory of cognitive aging. In G. E. Stelmach & P. A. Vroon (Series Eds.), *Advances in Psychology*: Vol. 28. North Holland, The Netherlands, Elsevier Science.

Salthouse, T. A. (1988). Cognitive aspects of motor functioning. *Annals of the New York Academy of Science*, *515*, 33-41

Schmidt, R. A., Zelaznik, H., Hawkins, B., Frank, J. S., & Quinn Jr, J. T. (1979). Motor-output variability: a theory for the accuracy of rapid motor acts. *Psychological Review*, *86*, 415.

Schmidt, R. A., & Wulf, G. (1997). Continuous concurrent feedback degrades skill learning: Implications for training and simulation. *Human Factors*, *39*, 509-525.

Schmidt, R. A., Heuer, H., Ghodsian, D., & Young, D. E. (1998). Generalized motor programs and units of action in bimanual coordination. In: Latash, M. L. (Ed.) Bernstein traditions II. *Human Kinetics*, Champaign IL, 329-360.

Seidler-Dobrin, R. D., & Stelmach, G. E. (1998). Persistence in visual feedback control by the elderly. *Experimental Brain Research*, *119*, 467-474.

Shannon, C., & Weaver, W. (1949). The mathematical theory of communication. Urbana: University of Illinois Press.

Shea, C. H., Park, J. H., & Braden, H. W. (2006). Age-related effects in sequential motor learning. *Physical Therapy*, *86*, 478-488.

Skinner, B. F., (1937). Two types of conditioned reflex: A reply to Konorski and Miller. *The Journal of General Psychology*, *16*, 272-279.

Skoura, X., Personnier, P., Vinter, A., Pozzo, T., & Papaxanthis, C. (2008). Decline in motor prediction in elderly subjects: Right versus left arm differences in mentally simulated motor actions. *Cortex*, *44*, 1271.

Slifkin, A. B., & Brener, J. (1998). Control of operant response force. *Journal of Experimental Psychology: Animal Behavior Processes*, *24*, 431.

Spirduso, W. W. (1975). Reaction and movement time as a function of age and physical activity level. *Journal of Gerontology*, *30*, 435-440.

Spirduso, W. W. (1980). Physical fitness, aging, and psychomotor speed: a review. *Journal of Gerontology*, *35*, 850-865.

Spirduso, W. W., & Clifford, P. (1978). Replication of age and physical activity effects on reaction and movement time. *Journal of Gerontology*, *33*, 26-30.

Stelmach, G. E., Goggin, N. L., & Amrhein, P. C. (1988). Aging and the restructuring of precued movements. *Psychology and Aging*, *3*, 151.

Swinnen, S. P. (2002). Intermanual coordination: from behavioural principles to neural-network interactions. *Nature Reviews Neuroscience*, *3*, 348-359.

Thompson, L. V. (2009). Age-related muscle dysfunction. *Experimental Gerontology*, *44*, 106-111.

Turvey, M. T. (1990). Coordination. *American Psychologist*, *45*, 938-953.

van Mourik, A. M., & Beek, P. J. (2004). Discrete and cyclical movements: unified dynamics or separate control? *Acta Psychologica*, *117*, 121-138.

Voelcker-Rehage, C. (2008). Motor-skill learning in older adults—a review of studies on age-related differences. *European Review of Aging and Physical Activity*, *5*, 5-16.

Walker, N., Philbin, D. A., & Fisk, A. D. (1997). Age-related differences in movement control: Adjusting submovement structure to optimize performance. *Journal of Gerontology: Psychological Sciences*, *52B*, P40-P52.

Welford, A. T. (1968). Fundamentals of skill. London: Methuen.

Welford, A. T., Norris, A. H., & Shock, N. W. (1969). Speed and accuracy of movement and their changes with age. *Acta Psychologica, 30*, 3-15.

Welford, A. T. (1988). Reaction time, speed of performance, and age. Annals of the New York Academy of Sciences, *515*, 1-17.

Winstein, C. J., & Schmidt, R. A. (1990). Reduced frequency of knowledge of results enhances motor skill learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *16*, 677.

Winstein, C. J., Pohl, P. S., & Lewthwaite, R. (1994). Effects of physical guidance and knowledge of results on motor learning: Support for the guidance hypothesis. *Research Quarterly for Exercise and Sport, 65*, 316-323.

Wisleder, D, & Dounskaia, N. (2007). The role of different submovement types during pointing to a target. *Experimental Brain Research, 176,* 132-149.

Woodworth, R. S. (1899). The accuracy of voluntary movement. *Psychological Review, 3,* 1-114.

Worden, A., Walker, N., Bharat, K., & Hudson, S. (1997). Making computers easier for older adults to use: area cursors and sticky icons. *In*: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM. 266-271.

Wulf, G., & Schmidt, R. A. (1989). The learning of generalized motor programs: Reducing the relative frequency of knowledge of results enhances memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*, 748.

Wulf, G., & Toole, T. (1999). Physical assistance devices in complex motor skill learning: Benefits of a self-controlled practice schedule. *Research Quarterly for Exercise and Sport*, *70*, 265-272.

Wulf, G., Shea, C., & Lewthwaite, R. (2010). Motor skill learning and performance: a review of influential factors. *Medical Education*, *44,* 75-84.