CONTROL OF WRIST AND ARM MOVEMENTS OF VARYING DIFFICULTIES

A Thesis

by

JASON BAXTER BOYLE

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

MASTER OF SCIENCE

December 2010

Major Subject: Kinesiology

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Approved by:

Chair of Committee:	Charles H. Shea
Committee Members,	David L. Wright
	Steven M. Smith
Head of Department,	Richard B. Kreider

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ABSTRACT

Control of Wrist and Arm Movements of Varying Difficulties. (December 2010)

Jason Baxter Boyle, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Charles H. Shea

Three experiments compared wrist and arm performance in a cyclical Fitts' target task. The purpose of Experiment I was to determine if movement kinematics differed for wrist/elbow flexion/extension movements to targets of varying difficulty. Participants were asked to flex/extend a manipulandum in the horizontal plane at the wrist and elbow joint in an attempt to move back and forth between two targets. Online knowledge of effector position was displayed as a visual trace on a projector screen. Target widths were manipulated with amplitude constant (16^{o}) in order to create Indexes of Difficulty of 1.5, 3, 4.5, and 6. Results failed to detect differences in elbow and wrist movements either in terms of movement time, movement accuracy, or kinematic characteristics of the movement. In studies that have reported difference in wrist and arm performance in Fitts' target tasks, experimenters have typically utilized visual amplification to counterbalance the small resulting wrist movements. The purpose of Experiments II and III was to investigate how changes in task parameters and visual gain play a role in providing a performance advantage for the wrist. In these experiments arm movement amplitude was increased to 32^{o} and wrist amplitude was decreased to 8^{o}. Results found similar overall movement times for arm and wrist movements. However, kinematic analysis of the movement revealed relatively large dwell times for wrist movements at IDs of 4.5 and 6. Removal of dwell time resulted in faster movement times for the wrist compared to arm. The results of these three experiments add to the limited literature examining how different effectors perform a Fitts' target task. These findings suggest that performance differences in past literature may be due to the visual amplification often used when arm, wrist, and finger movements are studied.

DEDICATION

This work is dedicated to the love of my life, Krystal.

ACKNOWLEDGEMENTS

I would like to sincerely thank my advisor, Dr. Charles Shea, for his unlimited attention, advice, and support throughout this project. I would also like to thank Dr. David Wright and Dr. Steven Smith for sitting on my committee, and providing me with valuable research tools from their lectures.

Thank you Mom and Dad for always being there for me with unwavering support and love.

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CHAPTER I

INTRODUCTION

In motor neuroscience, understanding the execution of goal directed action has been a leading topic of research for over one hundred years. Detailing the acquisition and execution of movement requires analysis of not only movement time and accuracy, but attention to the abundant control mechanisms involved before, during and after movement. Early studies examined the relationship between movement speed, target distance, target width, or both, in a task requiring participants to move between two defined target areas (Woodworth 1899, Fitts 1954, Annet et al. 1958, Crossman 1960, Welford 1968). These studies concluded that with manipulation of one or more of the three parameters (movement speed, distance between targets, and width of target), in order to remain accurate, participants had to adjust movement speed relative to the difficulty of the task. On the basis of their data, Paul M. Fitts (Fitts, 1954) offered a mathematical description of the relationship between movement accuracy as a function of task difficulty and movement time. This equation has become known as Fitts law and has been recognized as a valid predictor of human movement for the last sixty years. The movements utilized in these studies were cyclical in nature (i.e., participants made continuous movements in a defined time frame). Later investigations of Fitts' law involved discrete aiming tasks (single defined movements).

This thesis follows the style of *Journal of Motor Behavior*.

The comparison of cyclical versus discrete movement tasks sparked considerable debate and stimulating research from both perspectives for the last 50 years. Proponents of discrete tasks typically explain movement production using information processing approach, which argues knowledge from previous movements combined with anticipation of future movements' cause's discrepancies in cyclical studies (Fitts 1964, Schmidt et al 1979, 1988, 1998, Meyer et al. 1982, 1988, 1990, Plamondon 1993, Plamondon & Alimi 1997). In theory the discrete tasks can be thought of as the fundamental component for any movement (i.e., motor primitive). Theories regarding this basic movement component conclude that all movements, whether discrete or cyclical, are constructed from initial goal directed movements followed by corrective sub-movements (Crossman & Goodeve 1963, Meyer et al 1988, Plamondon & Alimi 1997). Conversely, proponents of cyclical tasks often explain movement production using a more dynamic approach which recognizes that the storage and dissipation of elastic kinematic energy plays a role in movement control (Crossman 1960, Fitts 1954, Welford 1968, Langolf et al. 1976, Turvey 1990, Kelso 1995, Buchanan et al 2003, 2004, 2006). Recent research which argues that discrete movements can be concatenated to form cyclical movements has switched attention to dependant variables (acceleration, dwell time, and harmonicity) that characterize the control processes of movement kinematics. (Guiard 1993, 1997, Buchanan et al 2003, 2004, 2006, Smits-Engelsman 2002).

The argument of discrete versus cyclical control of aiming movements has been studied for many years; however, little research has focused on Fitts original claim that performance comparisons of different effectors, (i.e., finger, wrist, and arm) should yield performance and/or control differences based on differences in the motor cortex (Fitts 1954, Penfield &

Rasmussen 1950). Penfield & Rasmussen's pivotal work on the composition of the motor cortex with respect to end effector illustrates a disproportionate system of sensation and control is in place (Penfield & Rasmussen 1950). A study by Langolf et al (1976) examined this claim by performing a Fitts task comparing performance of the fingers, wrists, and arms in a peg transfer and reciprocal tapping task. The authors' concluded that as task difficulty increased, a hierarchal system of control presented itself with fingers showing more effective performance (i.e., flatter slope) than wrist, and wrist greater than arm (Langolf et al. 1976). Similar conclusions were formed by Smits-Engelsman et al (2002) when comparing finger and wrist performance in cyclical and discrete tasks. Their findings conclude the fingers posses a greater index of performance, or a higher ability of information processing is available in the fingers compared to the wrist. Conversely, Balakrishnan & MacKenzie (1997) found equal performance for various effectors in a human-computer interaction study. Their study investigated finger, wrist and forearm abduction/adduction in a Fitts task with the aid of a computer generated visually displayed target. Their findings conclude the amount of information the fingers, wrist, and arm can process (in bits) is not significantly different in a Fitts target task. They argue that data reduction with small sample size and visual perception may have played a role in the performance variables found in the previous work (Balakrishnan & MacKenzie, 1997). Recent work by Kovacs et al. (2008) has also shown that performance violations in Fitts law can be created by amplifying the visual information the participants utilize to perform the task (Kovacs et al. 2008). Although Fitts law has been shown numerous times to accurately characterize the movement time and accuracy relationship, research regarding performance of differing effectors is still greatly unknown. The current study examined performance differences in wrist & elbow flexion in a cyclical goal directed Fitts target task. We argue that when comparing effectors in a Fitts task, all components of movement must be analyzed in order to fully understand the control processes involved. Performance was not only analyzed by traditional movement time, but also using kinematics measures calculations on movement half cycles (e.g., acceleration, peak velocity, dwell time, reversal, and harmonicity).

CHAPTER II

LITERATURE REVIEW

It is common knowledge that speed and accuracy must be considered in planning movements. Whether it is a seamstress threading a needle, a carpenter striking a nail with a hammer, or a surgeon using a scalpel, the speed of the movement affects the accuracy of the outcome and vice versa. This fundamental law that humans are forced to obey has been systematically studied in both the laboratory and field setting for the last 120 Years. The earliest documented scientific study of the speed-accuracy relationship was presented in a detailed manuscript by Woodworth in 1899. Implementing techniques and theories far advanced for his time, Woodworth proposed that *initial impulse* directed movements of the limb were under open loop control, and *current* control or positional feedback of the limbs helped participants hone their responding in order to achieve the accuracy required to reach a given target (Woodworth, 1899). This idea proposes that the initial impulse directs the limb toward a target and current control initiates small sub-movements to maintain accuracy of the movement. In one of Woodworth's tasks, participants were asked to perform repetitive line drawing between two targets while staying in pace with a metronome. Manipulations in this study examined different distances between targets, metronome speed, right/left hand performance, and eyes open/closed. Following the completion of this study, Woodworth concluded that participants were less accurate as movement speed increased; right hand performance was greater than left hand performance, and performance was significantly hindered when the participants' eyes were closed. Woodworth's research, though groundbreaking, was not advanced further until the seminal work by Fitts' (Fitts, 1954).

Fitts Law

Since its publication in 1954, Paul M Fitts' now classical paper entitled "*The Information Capacity of the Human Motor System in Controlling the Amplitude of Movement*" has been cited more than 2,500 times, and has stimulated research and theory on the processing and control of movements of different difficulties. Expanding the current theories of his time (Shannon & Weaver 1949; Hick 1952; Hyman 1953), Fitts (1954) applied information theory to the study of goal- directed movement. Fitts stated, "we cannot study mans motor system at the behavioral level in isolation from its associated sensory mechanism." Fitts developed an experimental design that not only examined the behavioral aspects of human performance, but the interrelated relationship of this behavior with mans sensory perception (Fitts, 1954). The experimental design was to apply Shannon's Theorem 17 to the control of human movement, and generate an empirical equation that best represents performance constraints. To accomplish this Fitts' had participants' rapidly alternate pressing the tip of a stylus onto two defined target areas for a period of 20 seconds. To ensure an accurate reading of performance, the target areas consisted of three zones of performance (under shoot, correct, and over shoot). The two target areas had an available width of correct response (W), and were separated by a distinct distance between them measured from the center of each target (A). Participants were asked to alternately hit the tip of the stylus in the target areas as rapidly as they could, while still making sure they accurately struck within the bounds of the target. If the participants had greater than 5% error, their data was omitted from the study. Fitts noted that experimental manipulations of W and/or A, resulted in increased or decreased in attention demand in order to perform the task accurately. This manipulation was shown to have a direct linear relationship with the participants movement time (MT). Disc transfer and peg transfer tasks, following similar manipulations from the first task, were also examined in his series of experiments. These tasks yielded a similar pattern of results. Following the completion of this work, mathematical analysis of the effect of target width (W) and movement distance (A) on movement time was used to create an index characterizing the difficulty of the movement. This index has come to be known as the index of difficulty (ID). The term ID is a representation, in bits of information that have to be processed to achieve a given task. The index is calculated by the equation ID= Log_2 (2A/W). Where A represents the amplitude or distance between the targets and W represents the width of the targets area. Both A&W are independent variables that when manipulated increase or decrease the value of ID, which ultimately affects MT as represented in the equation MT = a + b (ID). The a and b in Fitts' equation represent empirical constants of intercept (a) and slope (b). Comparing MT to ID yields the trademark linear relationship of a Fitts' task.

Following the publication of Fitts' theory, investigators began replicating the model with much success (Annet et al. 1958, Crossman, 1960, Welford, 1968). However, in a limited number of cases, differing relations between A & W were shown (Andriessen, 1960, Vredenbregt, 1959) leading Fitts to reanalyze the construction of the task. Realizing that to date, all previous studies on movement speed/accuracy tradeoffs required participants move in a cyclical fashion (Fitts 1954, Crossman 1960, Welford 1968), Fitts investigated how this task may have underlying interferences that may be removed if the task were discrete, or simply, a single movement (Fitts & Peterson 1964). Continuing with the apparatus from the previous experiment, participants were instructed to position a stylus directly in between the target areas. A set of lights, determining left or right target, informed the subject which target to move to. Receiving the cue from the light, the participants would move as fast as possible to the center of the target where they would come to a complete stop. Following each individual trial, the stylus was brought back to the center in anticipation of the next movement. After comparing slopes of MT in both (cyclical and discrete), Fitts concluded that cyclical movements were plagued by the knowledge, or lack there of, of the previous movement and anticipation of future movements (Fitts & Peterson 1964) ultimately leading to slower movement times.

Discrete vs Cyclical Fitts' Task

Target directed movement studies over the past 50 years have typically explained using two different theoretical perspectives: Information processing models which characterize movements as discrete segments (Fitts 1964, Schmidt et al 1979, 1988, 1998, Meyer et al. 1982, 1988, 1990, Plamondon 1993, Plamondon and Alimi 1997) and dynamic models which characterize movements as cyclical (Crossman 1960, Fitts 1954, Welford 1960, Langolf et al. 1976, Turvey 1990, Kelso 1995, Buchanan et al 2003, 2004, 2006). Proponents of discrete tasks argue single movements eliminate any discrepancies that may hinder performance in cyclical movement tasks. Knowledge of past performance and anticipation of future movements result in noise in the CNS, ultimately affecting the strength of motor command signals to the limbs. Note also that movement time in reciprocal and discrete movements have in some cases been measured differently (Langolf et al 1976, Balakrishnan & MacKenzie 1997). In discrete tasks movement time is typically measured from the initiation of the movement to the termination of the movement (Fitts & Peterson 1964). In some experiments this is calculated as the time from the release of a start button to the depression of a stop (target) button or loss of contact in leaving the start position to contact in the target. In the majority of more recent experiments using discrete tasks movement time is determined from kinematic markers on the velocity trace (Buchanan et al 2003). Using this method movement time is measured backward from the point of peak velocity until movement velocity falls below some preset value (i.e., 5%) of peak velocity and movement termination is measured forward from peak velocity using the same rules. Movement time is then essentially the difference between the start and end of the movement. Often researcher studying reciprocal movement tasks also use this kinematic method of determining movement time. However in some experiments the experimenter simply determined the number of movements completed within a set time period and determines movement time by simply dividing the number of movements by the total amount of time or calculates movement time from the initiation of one movement to the initiation of the next (Buchanan et al 2003). These latter methods include dwell time in the movement time calculation. Dwell time is essentially the time between movements, but may represent an important interval especially in high ID movements. For example, numerous experiments using discrete tasks have demonstrated that reaction time increases with increased movement difficulty (e.g., Henry & Rogers, 1960; Klapp, 1996; Rosenbaum, 1980; Sidaway, 1991). Thus, a longer time may be required to prepare the next movement in the series as the difficulty increases and this increase may be different for different effectors In a cyclical task, especially at higher ID values, participants display a moment of non-movement once the target has successfully been entered (i.e., dwell time). This small moment of non-movement is the subject's preparation for reversal and has traditionally been labeled dwell time (Fitts & Peterson 1964, Guiard 1997, Buchanan et al 2003, 2004, 2006). In either movement condition, as the subject nears the target, dissipation of kinematic energy must happen in order for the limb to come to a halt in the target area. In the cyclical task, the dissipation of energy has to coincide with the anticipation of the following movement reversal, especially at high ID values, leading to longer dwell times. Analysis of movement time in a cyclical task without removal of dwell time may present biased performance values, leading some researchers to conclude the discrete task as the most accurate tool of movement analysis. At low ID values (easy), cyclical movements have been shown to have better performance than discrete movements due to the muscle/tendon ability to utilize stored elastic energy (Guiard 1993, 1997). Guiard examined what factors aided the limb in the cyclical condition and later termed the fluent motion of the limb as movement harmonicity. Recent work examining harmonicity of limb motion has shown discrete and cyclical control is a direct function of the constraints imposed by the difficulty of the task. A value ranging from 1-0, 1 meaning true cyclical harmonic movement, 0 meaning discrete non-harmonic movement, and 0.5 the demarcation point, is used to analyze switching of control processes as ID increase and vice versa (Guiard 1997, Buchanan et al 2003, 2004, 2006). A critical ID (IDc) value of 4.44 was established by Buchanan et al. (2003) as the crossover of control processes. Movement constraints below this value are consistent with harmonic motion with relatively minimal dwell times. As the constraints span the IDc, dwell time drastically increases as dissipation of energy becomes an important factor in ensuring accuracy (Adam & Paas 1996, Guiard 1993, 1997, Buchanan et al 2003, 2004, 2006).

Performance of Differing Effectors in a Fitts' Task

Even before methods of brain imaging were available, researchers have proposed performance differences in effectors, such as the wrist or fingers, would exhibit a greater level of control than the arm or leg do to the functionality of the effectors neural innervations (Fitts 1954, Penfield & Rasmussen 1950). Even though this comment was assumed over 50 years ago, little research has examined this question and limited studies that have tested this, have yielded conflicting results (Gibbs 1962, Hammerton & Tickner 1966, Langolf et al. 1976, Balakrishnan & MacKenzie 1997, Smits-Engelsman et al 2002). In 1976, Langolf et al. studied finger, wrist, and arm movements using Fitts' peg transfer and reciprocal finger tapping task. Their results agreed with Fitts' original claim and concluded that the slope for finger and wrist performances was less than that found for arm performance. In other words, arm movements were slower than finger and wrist movement to the same ID and this difference increased as the ID increased. Comparing Langolf's findings to research on motor cortex control (Penfield & Rasmussen 1950), one would be hesitant to argue that these findings are not true. However, previous work in human computer interaction (HCI) has concluded that the amounts of bits the fingers, wrists, and arms can process in a Fitts aiming task are not significantly different, arguing differing effectors may employ similar control processes (Balakrishnan & MacKenzie 1997). Their study had participants perform adduction/abduction movements with the finger, wrist, and forearm to a visually displayed target on a computer screen. Balakrishnan & MacKenzie argue the small sample size in Langolf's study may be a deciding factor in the data analysis results. Another argument to Langolf's results is the peg transfer task the participants were asked to perform was presented in a visually amplified (10x) environment by looking through a stereomicroscope. Recent work by Kovacs et al. (2008) has shown that an increase in the visual gain of a Fitts' task can result in a decrease in MT, especially at high IDs (ID>4.5) or, a violation of Fitts Law (Kovacs et al. 2008). Though altering the visual gain of the task was the purpose of the Kovacs et al study, investigators unbeknownst to this visual violation, may conclude their findings were independent of the visual aspect of their task. Recent work by Smits-

Englesman et al (2002) compared finger and wrist performance in both a cyclical and discrete task condition. Their findings conclude that the fingers can process higher bits of information (index of performance) per second than the wrist in a cyclical Fitts task. The difference in index of performance was only shown in the smallest of the three target conditions (.22cm). Although the previous study mentioned does not investigate the arm, it is important to note that the authors agree with the hypothesis of a hierarchical system of motor control for different muscle effectors.

Summary

The limited number of studies combined with conflicting results led us to believe that little is still known about the control processes of different effectors during performance of a Fitts' task. Future studies using different effectors, more specifically wrist versus arm control; need to consider implications of the perceptual and control effects noted in the current literature. The sample size must be adequate to make a statistically significant conclusion about the findings. The visual gain perceived must be controlled throughout both tasks (wrist & arm) so that any perceptual effect can be appropriately categorized. Knowledge of wrist and arm kinematics will undoubtedly play a valuable role in comparison of different ID's performance.

CHAPTER III

EXPERIMENT I

Introduction

Control of speed and accuracy in goal directed movement has been repeatedly shown to follow a similar mathematical equation which has been labeled Fitts Law. Numerous investigators have examined these phenomena in cyclical (Crossman 1960, Fitts 1954, Welford 1960, Langolf et al. 1976, Turvey 1990, Kelso 1995, Smits-Engelsman et al 2002, Buchanan et al 2003, 2004, 2006), and discrete (Fitts 1964, Schmidt et al 1979, 1988, 1998, Meyer et al. 1982, 1988, 1990, Plamondon 1993, Plamondon and Alimi 1997, Smits-Engelsman et al 2002) aiming tasks. Recent studies of movement kinematics and harmonicity have found at ID levels below a critical value labeled the IDc (4.4) movement production involves preplanned control which takes advantage of the storage and utilize of kinetic energy in what has been termed cyclical motion. When the ID increases above IDc movement production switches to the utilization of more feedback during the movement control in order to achieve the increased accuracy requirements (Guiard 1997, Buchanan et al 2003, 2004, 2006) which has been termed discrete motion. However, the majority of research looking at the kinematic and kinetic characteristics of cyclical movements across varying difficulties has utilized arm movements. The goal of the present research was to determine if these characteristics are similar for arm and wrist movements. It is possible that wrist movements because of the increased neural control capabilities and decreased mass might switch from continuous/preplanned control to more discrete/on-line control at different IDc. Further, if this occurs it is possible the movement time – ID linearity common to Fitts' tasks may be compromised. Literature examining Fitts' original claim that different effectors could exhibit control differences due to motor cortex availability have found conflicting results (Langolf et al. 1976, Balakrishnan & MacKenzie 1997, Smits-Engelsman et al 2002). A study, for example, by Langolf et al (1976) investigated movement trajectories in a Fitts' task by having participants perform a peg transfer and reciprocal tapping task. The authors noted that as movement distance and difficulty increased, the participants engaged in exclusive finger, wrist, or arm movements. Final movement time values were labeled based upon the effector that executed the movement. Their results indicated differences in movement time between all effectors, with the fastest movements for a given ID being performed by the fingers and slowest movement by the arm with this difference increasing as movement difficulty increased. Balakrishnan & MacKenzie (1997) also investigated control processes in the finger, wrist and arm in a human computer interaction Fitts' task. Participants were asked to reciprocally move a cursor between two displayed target areas by moving a custom apparatus with the finger, wrist, and forearm in the horizontal plane. However, their results indicated that performance (in bits) for the arm and wrist did not differ significantly from those for the finger. It is possible that the differences in the tasks, movement requirements (A and W), and/or the feedback provided may account for these differences.

Method

Participants

Participants (5 male, 4 female) between the ages of 18 and 26 yrs of age volunteered to participate in the experiment for course credit. The experimental protocol for this experiment was approved by the IRB at Texas A&M University. The participants had no prior experience with the experimental task and were not aware of the specific purpose of the study. Informed consent was obtained prior to participation in the experiment. Each participant received class credit for their participation.

Apparatus

The apparatus consisted of a horizontal lever supported at the proximal end by a vertical axle that turned almost frictionless in a ball-bearing support. The support was affixed to the right sides of the midline of the table, allowing the levers to move in the horizontal plane over the table. At the end of the lever, a vertical handle was fixed. The handle's position could be adjusted so that, when grasping the handle, the participant's elbow could be aligned with the axis of rotation. A potentiometer was attached to the lower end of the axis to record position of the lever and its output was sampled at 100 Hz. A wooden cover was placed over the table to prevent participants from seeing the lever and their arm. A video projector was used to display the stimulus onto the wall facing the participant. Participants were seated at about 2 meters from the wall and a 1.64 x 1.23 m image was projected on the wall (see Figure 1).

Procedure

Participants were seated at a table with their forearm or wrist (depending on the condition) resting on a horizontal lever that restricted elbow/wrist motion to flexion-extension in the horizontal plane (Figure1). A wooden handle was attached to the distal end of the lever for the arm condition and was positioned closer to the proximal end for the wrist task. The handle adjusted from 31 to 36 cm from the axis of rotation to ensure the participants' elbow or wrist joint (depending on the condition) were centered with the axis of rotation proximal. Flexing the elbow or wrist horizontally moved the lever towards the body and extending the elbow or wrist horizontally moved the lever away from the body. Elbow/wrist motion was recorded by a potentiometer (sampled at 200 Hz) attached to the horizontal lever. Participants were seated on a height adjustable chair with the horizontal eye line corresponding with the midway point between two targets projected on a screen. Vision of the right arm/wrist was obstructed by a board placed 20cm above the table top. Although vision of the arm/wrist motion was occluded, the potentiometer signal was provided as on-line visual feedback in the form of a cursor that represented flexion-extension motion of the elbow or wrist. The cursor and two targets were generated with custom software and displayed with a projector mounted above the participant. Movement amplitude for the right arm was fixed at 16º and four target widths (11.3 º, 4 º, 1.415 º, and .5 º) were used to create ID conditions, ID = 1.5, ID = 3, ID = 4.5, and ID = 6, spanning the IDc. Movement amplitude for the right wrist was fixed at 16 º and four target widths (11.3 º, 4 º, 1.415 º, and.5 º) were used to create ID conditions, ID = 1.5, ID = 3, ID = 4.5, and ID = 6. The participants moved the horizontal lever back and forth so that the cursor projected on the wall in front of them moved between four lines that defined the two target areas. The two targets were defined by a solid blue fill creating two rectangular shaped areas enhanced by a black background behind them. The participants performed three consecutive 15 second trials for each of the four IDs' (1.5, 3, 4.5, and 6) with either the arm or wrist. After completion of the first 12 trials, the participants switched to either the arm or wrist depending on the initial procedure performed. The forearm was placed on a pad connected to the table, and the participants were instructed to leave the arm down at all times to ensure only the wrist was activated in the wrist condition. Participants were asked to move as fast and accurately as possible on the first two trials in preparation for the third trial labeled "the test", where participants were asked to produce their greatest level of performance. A 15 sec rest interval followed each trial. Following completion of the 12 trials, the exact program the participants completed was run again. On the next 12 trials, the participants were asked to approach each individual trial as if it were trial number 3, "the test", in order to record their greatest level of performance. In the second round of trials, the trial with the lowest percentage of error was recorded as the subject's performance data.

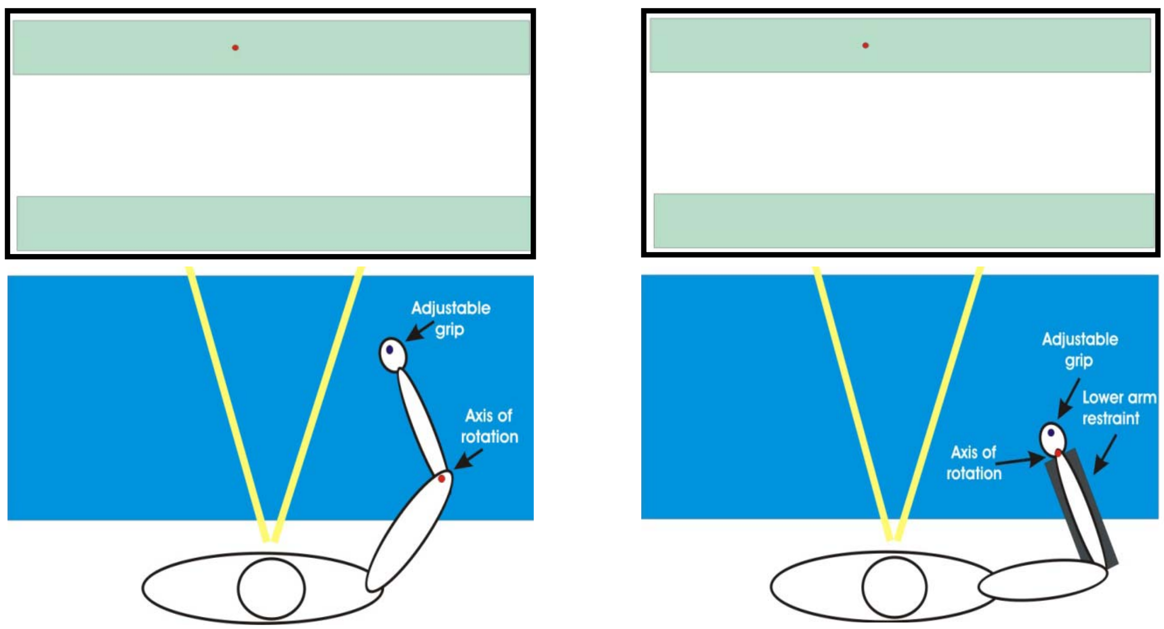

Figure 1. Illustration of the set-up (top view) for the arm (left) and wrist (right) conditions and feedback presentation (top). Note that the position of the limb was displaced as a cursor on the display and the targets were indicated by the shaded areas.

Measures & data analysis

All data reduction was performed using MATLAB. The potentiometer signal representing limb displacement, limb velocity and acceleration was filtered with a second order dual-pass Butterworth filter with a cutoff frequency of 10 Hz. All dependant measures were computed on a half-cycle basis with each half cycle representing a different movement direction of the limb (extension or flexion). Onset and offset of each movement following reversal was used to calculate limb acceleration, total movement time, and dwell time. In each half cycle, peak velocity of the movement was identified and traced back to 5% of its value following the previous movements' reversal, equaling movement onset. Movement offset was calculated by identifying peak velocity and tracing forward to a value of 5% peak velocity before reversal for the next movement. Utilizing the parameters of onset and offset, movement time was calculated by the equation, MT = movement $offset_i$ – movement $onset_i$. In a cyclical task, especially as ID increases, the amount of time spent reversing the movement in preparation for the following movement will increase what is known as dwell time, DT = movement $onset_{i+1}$ – movement $offset_i$. Calculating movement onset within a half cycle to peak velocity gave limb acceleration. Peak velocity to movement offset equaled limb deceleration. Two measures of movement endpoint were labeled constant and variable error. Measuring within subject mean difference between movement endpoint and target center gave the value for constant error. The within participants standard deviation of the constant error gave the participants variable error. MT1, MT2, dwell time, and % TPV were analyzed in separate Effector x ID analyses of variance (ANOVAs) with repeated measure on both factors. Duncan's new multiple range test and simple main effects analysis were utilized when appropriate as post-hoc procedures to follow up on significant main effect and interactions, respectively. In addition, a regression analysis was conducted on MT1 and MT2 to determine the slopes and degree of linearity under the arm and wrist conditions. An α=.05 was used for all tests.

Results

Examples of normalized displacement and velocity for each Limb x ID condition for one participant are provided in Figure 2. Normalized displacement and velocity profiles for the arm and wrist movements at IDs 1.5 and 6 for one participant are provided in Figure 3.

Mean MT1 (A), MT2 (B), dwell time (C), and percent time to peak velocity (D), are provided in Figure 4.In Figure 3, the time at which movement initiation, peak velocity, and movement termination occurs are depicted.

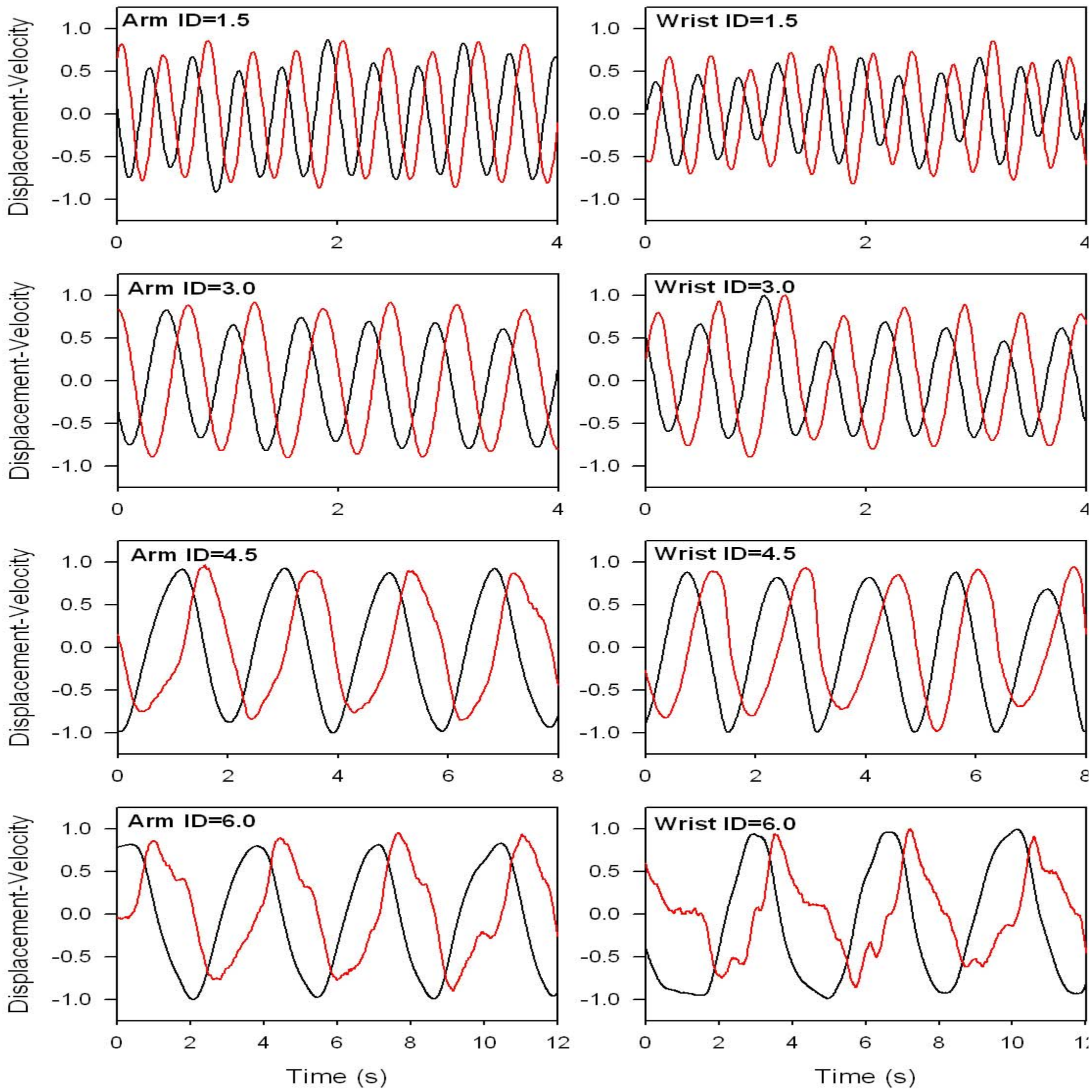

Figure 2. Examples of movement displacement (black) and velocity (red) for arm (left) and wrist (right) movements at each ID in Experiment I.

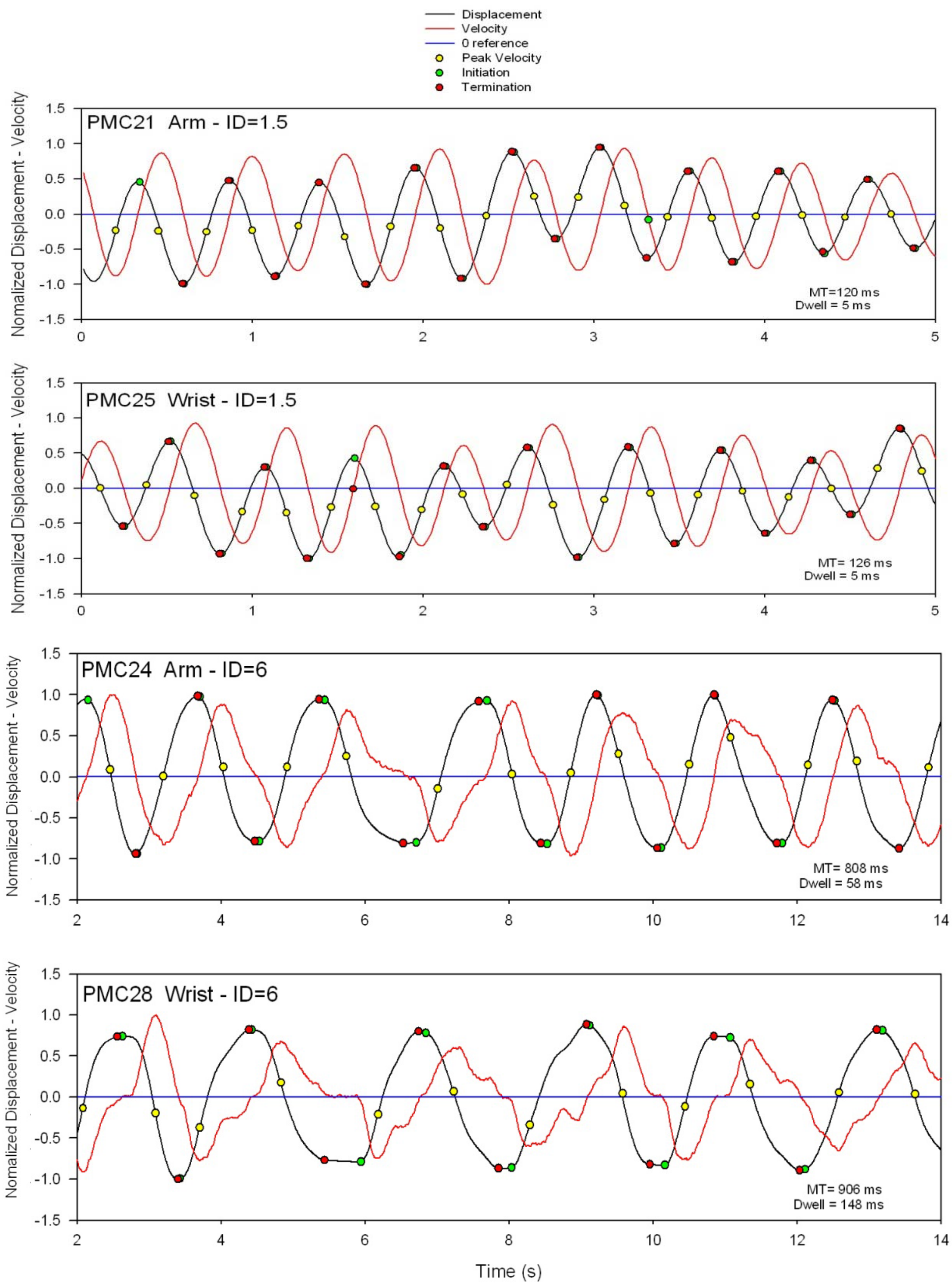

Figure 3. Example of movement displacement (black) and movement velocity (red) for a trial with the arm (top) and wrist (bottom) with an ID 1.5 and 6. Movement onset (green), peak velocity (yellow) and movement termination (red) based on movement velocity are indicated on the movement displacement trace.

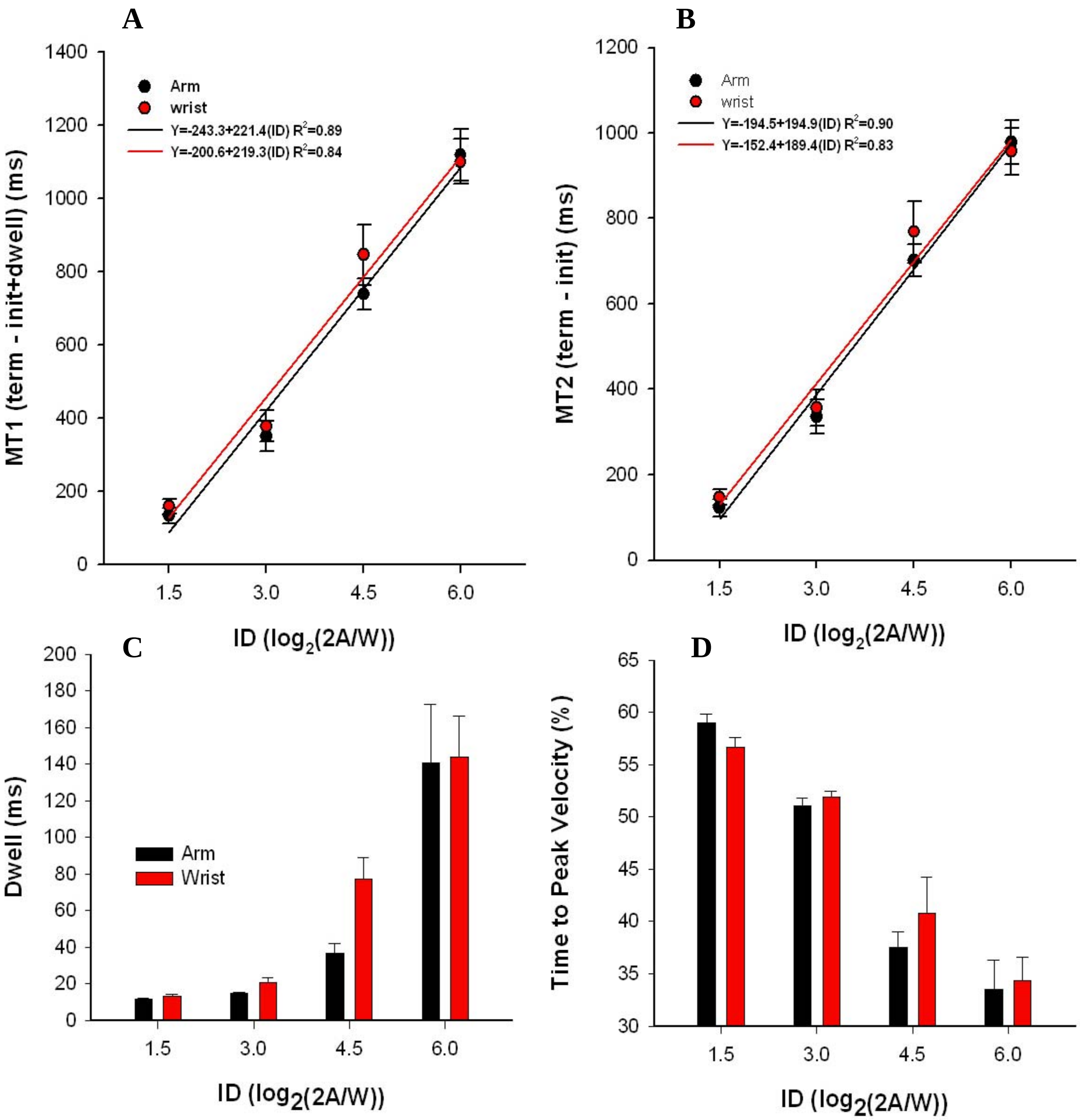

Figure 4. Mean MT1 (A), MT2 (B), dwell time (C), and percent time to peak velocity by effector (arm and wrist) and ID (D) in Experiment I. Regression lines and R2 are provided for MT1 and MT2.

Movement time 1 (MT1)

The analysis indicated a main effect for the ID F(3,54)= 192.26, p<.01. The main effect of effector $F(1,54)=2.07$, $p>.05$, and the Effector x ID interaction, $F(3,54)=0.49$, $p>.05$ were not significant. Duncan's new multiple range test indicated that MT1 increased for each ID.

Movement time 2 (MT2)

The analysis indicated a main effect for the ID $F(3,54)= 186.36$, $p<.01$. The main effect of effector $F(1,54)=1.21$, $p>.05$ and the Effector x ID interaction, $F(3,54)=0.27$, $p>.05$ were not significant. Duncan's new multiple range test on ID indicated that MT2 increased for each ID.

MT1 and MT2 regression analysis

The regression analyses for the arm and wrist using MT1 data indicated strong linear relationships between MT1 and ID for the arm, $F(1,18)=141.23$, $p<.05$, $R^2=.90$, and wrist, $F(1,18)=135.2$, $p<.05$, $R^2=.89$. The regression analysis for the arm and wrist using MT2 data also indicated strong linear relationships between MT2 and ID for the arm, $F(1,18)=178.9$, $p<.05$, $R^2=.92$, and wrist, $F(1,18)=124.8$, $p<.05$, $R^2=.88$. The slope of the regression line (β_1) for the arm was minimally reduced from the MT1 to MT2 analysis (237.5 ms and 205.2 ms, respectively). Similarly, β_1 for the wrist was minimally reduced from the MT1 to MT2 analysis (239.7 ms and 205.5 ms, respectively).

Dwell time

The analysis indicated a main effect for the ID $F(3,54)= 36.23$, $p<.01$. The main effect of effector $F(1,54)=2.14$, $p>.05$ and the Effector x ID interaction, $F(3,54)=0.75$, $p>.05$ were not significant. Duncan's new multiple range test on ID indicated that similar dwell times for IDs=1.5 and 3. Dwell time increased for ID=4.5 with substantial increases again for ID=6.

Percent time to peak velocity (% TPV)

The analysis indicated a main effect for the ID $F(3,54)= 85.69$, $p<.01$. The main effect of effector $F(1,54)=0.11$, $p>.05$ and the Effector x ID interaction, $F(3,54)=1.01$, $p>.05$ were not significant. Duncan's new multiple range test on ID indicated that %TPV decreased for each ID as IDs increased.

Discussion

Experiment I was designed to investigate performance of differing effectors in a cyclical Fitts' task. Participants were instructed to move a cursor between two defined target areas as quickly and accurately as possible by flexing and extending at the wrist and elbow joint. Their performance was displayed as real time online feedback in the form of a cursor leaving a trace line displayed on the screen. The same movement distances, and target widths (IDs) were in the arm and wrist conditions. Visual gain was also constant between the arm and wrist conditions to ensure the same feedback resolution was used across conditions. Performance was measured as total movement time for one trial which we label (MT1) and movement time minus dwell time which we label (MT2). The results failed to detect differences in elbow and wrist movements either in terms of movement time, movement accuracy, or kinematic characteristics of the movement. These results suggest that if provided equal physical and visual representations of the target task control processes and movement outcomes will be similar for the wrist and elbow. These findings are contrary to the previously mentioned studies of Langolf et al (1976) and Smits-Engelsman et al (2002) which found movement time for the wrist to be increasingly faster that the arm as ID was increased. Further, these findings raises questions about the task constraints, procedure, data analysis and ultimately the conclusions presented in these experiment. One possible problem with these conclusions are that assumptions are formed about differences in finger, wrist, and arm performance by comparing movement time on separate tasks that are independent of each other. (cyclical tapping & discrete peg transfer) (Langolf et al, 1976). Also, differences in target width, amplitude, and visual perception could have played a role in these author's findings (Langolf et al, 1976, Smits-Engelsman et al, 2002). Recent work by Kovacs et al. (2008) has shown that an increase in visual gain will improve movement time at higher IDS (i.e., ID=6) creating a violation of linearity of typical Fitts' law performance. These violations, specifically at the wrist, are investigated in Experiment II.

CHAPTER IV

EXPERIMENT II

Introduction

The data from Experiment I indicated similar movement times (MT1, MT2) for both effectors (arm/wrist) at each ID. Although the slope was slightly reduced for MT2 relative to MT1 the pattern was similar for both effectors. It is interesting to note that even though one might expect participants to be more accustomed to utilizing elbow movement for rapid ballistic movements no differences were noted at the lower IDs. It is also interesting that although the area of the motor cortex devoted to the wrist is larger than that devoted to the elbow no advantage in terms of movement time was noted for the wrist. The bottom line was that elbow and wrist movements, which involved the same amplitudes and target widths (IDs) and visual feedback scaled in the same, produced similar patterns of movement.

The questions now arise concerning previous findings of advantages in terms of MT for the wrist relative to the arm found in previous experiments (Langolf et al., 1976; Smits-Englesman et al., 2002). The major differences in the Experiment I and the previous studies involved movement amplitude/target width used to create the various ID conditions and the manner in which the feedback was provided. In Langolf et al. (1976) study, movement times for three participants were examined in a peg transfer task and Fitts original reciprocal tapping task. The peg transfer task consisted of two very small target widths (.076mm, 1.07mm) and target amplitudes (.25cm, 1.27cm). The dimensions of the peg transfer task were so small that it had to be performed under a stereomicroscope at a power of 7. The reciprocal tapping task followed Fitts original dimensions of target widths (.64cm, 1.27cm, 2.54cm, 5.08cm) separated by amplitudes (5.08cm, 10.2cm, 20.3cm, 30.5cm). Langolf et al.

(1976) noticed the participants utilized the fingers in the smallest of the peg transfer task, the wrist in the largest peg transfer, and the arm in the reciprocal tapping task. This examination led the researchers to conclude the movement time in these conditions were a result of the effector that was engaged. Smits-Englesman et al (2002) had participants perform a reciprocal line drawing task with the fingers and wrist. The amplitude of the target was held at a constant 2.5 cm. Different ID values were created by manipulating the widths of the target (.22cm, .44cm, .88cm). Balakrishnan & MacKenzie (1997) had participants perform adduction/abduction with the finger, wrist, and forearm in a cyclical Fitts' task. The target the participants moved in and out of was displayed on a computer screen. The IDs of 1.32 to 4.64 were created by target widths of (3mm, 6mm, and 12mm) with amplitude distances of (18 mm, 36 mm, 72 mm). It is clear that in the three mentioned studies, participants were asked to make very small movements. Also, two of the tasks mentioned were so small that the task had to be visually amplified (Langolf et al, 1976, Balakrishnan & MacKenzie, 1997). Note that recent literature has shown that performance in Fitts task can be influenced by visual amplification especially at higher IDs (Kovacs et al 2008). The purpose of Experiment II was to design an experiment that more resembles the movements and visual constraints imposed on the participants in the previous literature and examine how these smaller movements in a visually amplified environment enhanced performance.

Method

Participants

Participants (4 male, 6 female) between the ages of 18 and 24 yrs of age volunteered to participate in the experiment for course credit. The experimental protocol for this experiment was approved by the IRB at Texas A&M University. The participants had no prior experience with the experimental task and were not aware of the specific purpose of the study. Informed consent was obtained prior to participation in the experiment. Each participant received class credit for their participation.

Apparatus

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

Procedure

Movement amplitude for the right arm was fixed at 32º and four target widths (22.6 º, 8 º, 2.83 º, and 1 º) were used to create ID conditions, ID = 1.5, ID = 3, ID = 4.5, and ID = 6, spanning the IDc. Movement amplitude for the right wrist was fixed at 8 º and four target widths (5.65 º, 2 º, .71 º, and .25 º) were used to create ID conditions, ID = 1.5, ID = 3, ID = 4.5, and ID = 6. Do to the small A&W value for the wrist; the visual display was amplified to match the dimensions of the display for the arm condition. The participants moved the horizontal lever back and forth so that the cursor projected on the wall in front of them moved between four lines that defined the two target areas. The two targets were defined by a solid blue fill creating two rectangular shaped areas enhanced by a black background behind them. Besides the change in A & W, the procedure followed the same criteria as Experiment I.

Measures & data analysis

All data reduction and analyses were performed as in Experiment I.

Results

Examples of normalized displacement and velocity for each Limb x ID condition for one participant are provided in Figure 5. A more detailed illustration of normalized displacement and velocity for arm and wrist movements at ID=6 is provided in Figure 6. In this figure the time at which movement initiation, peak velocity, and movement termination occurs are depicted. Figure 7 provides mean MT1 (a), MT2 (b), dwell time (c) and %time to peak velocity (d).

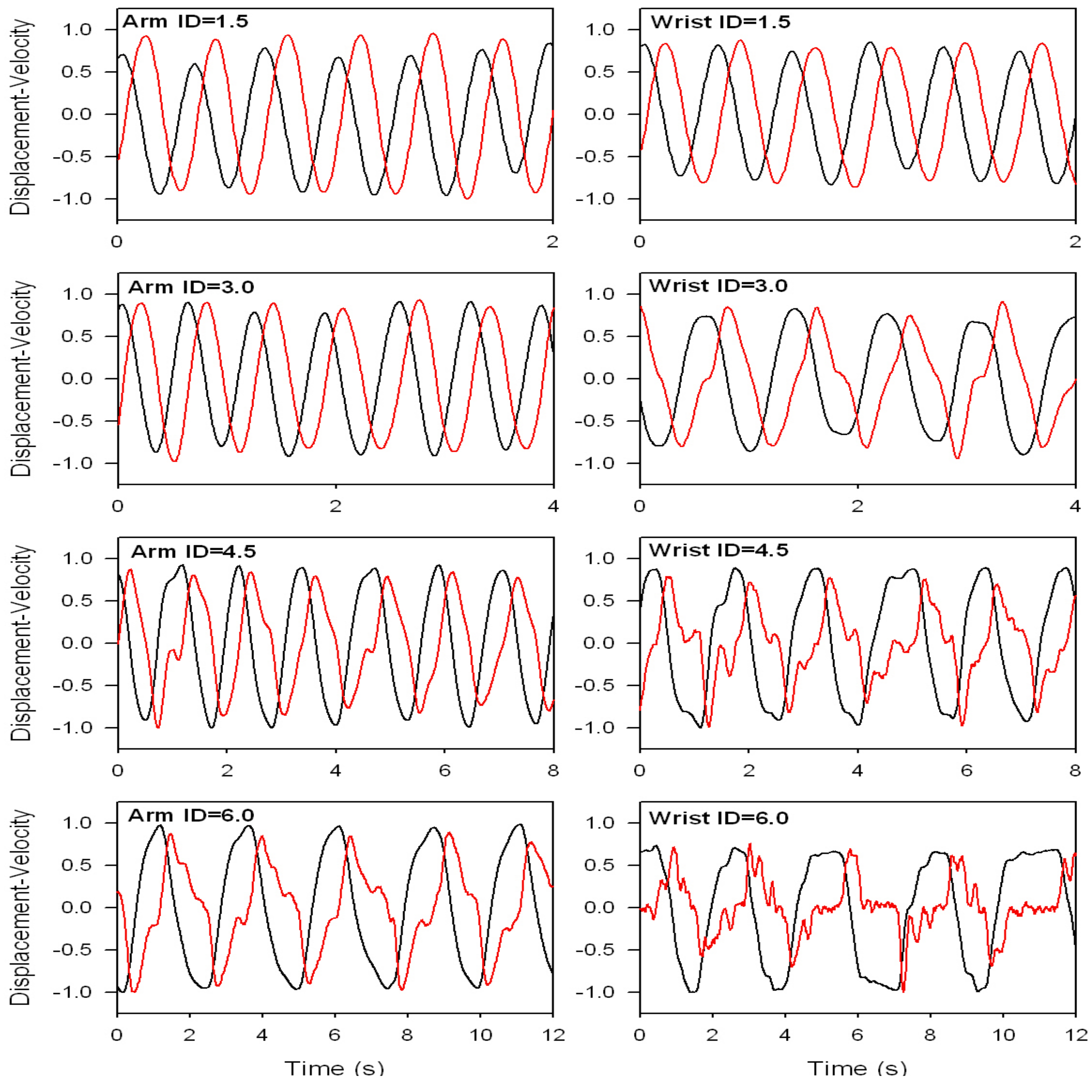

Figure 5. Examples of movement displacement (black) and velocity (red) for arm (left) and wrist (right) movements at each ID in Experiment II.

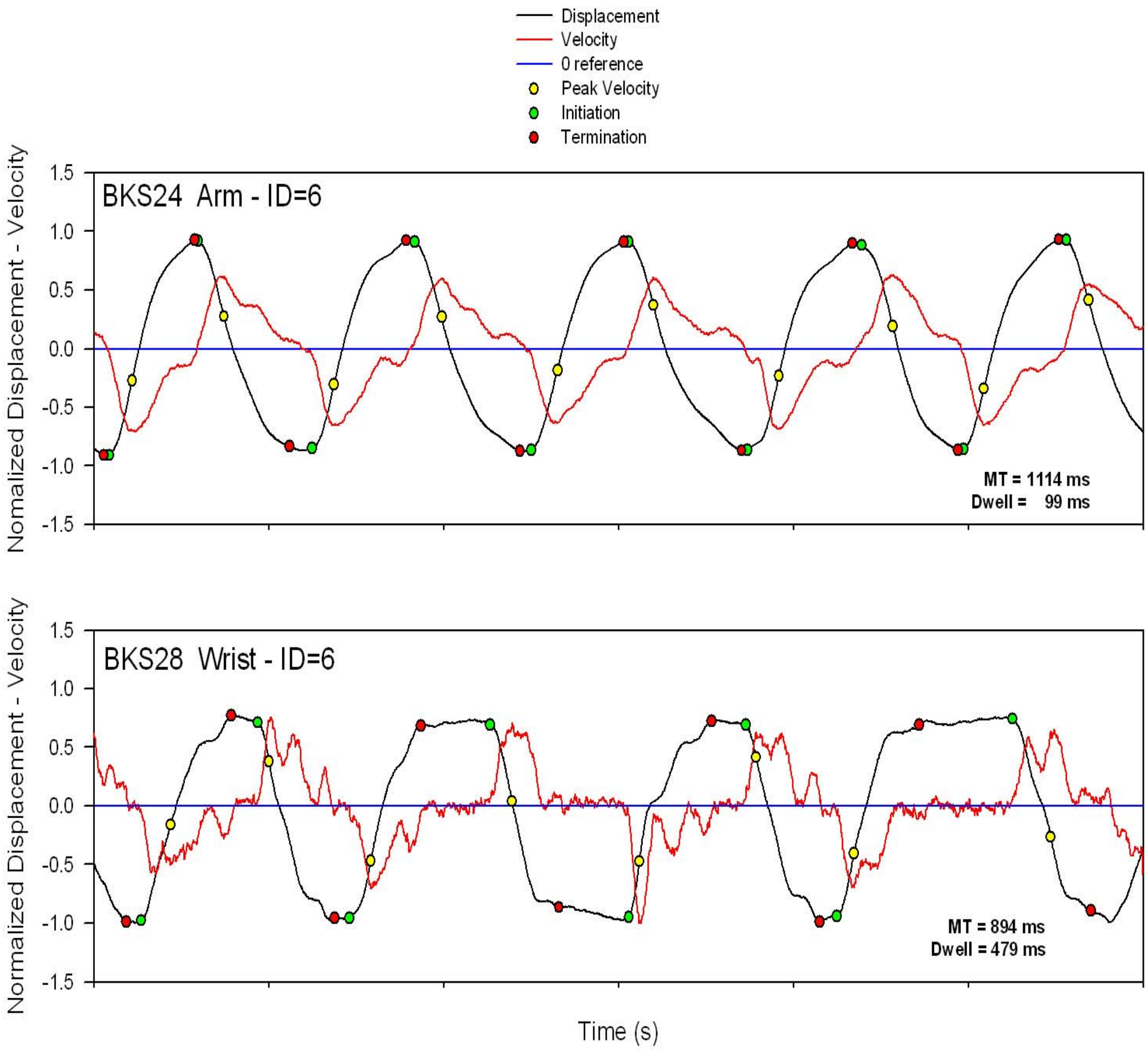

Figure 6. Normalized displacement (black) and velocity (red) for one participants using the arm (top) and wrist (bottom) at ID=6. Movement onset (green), time of peak velocity (yellow), and movement offset (red) are depicted. Note that dwell time is from the offset of one movement to the onset of the next.

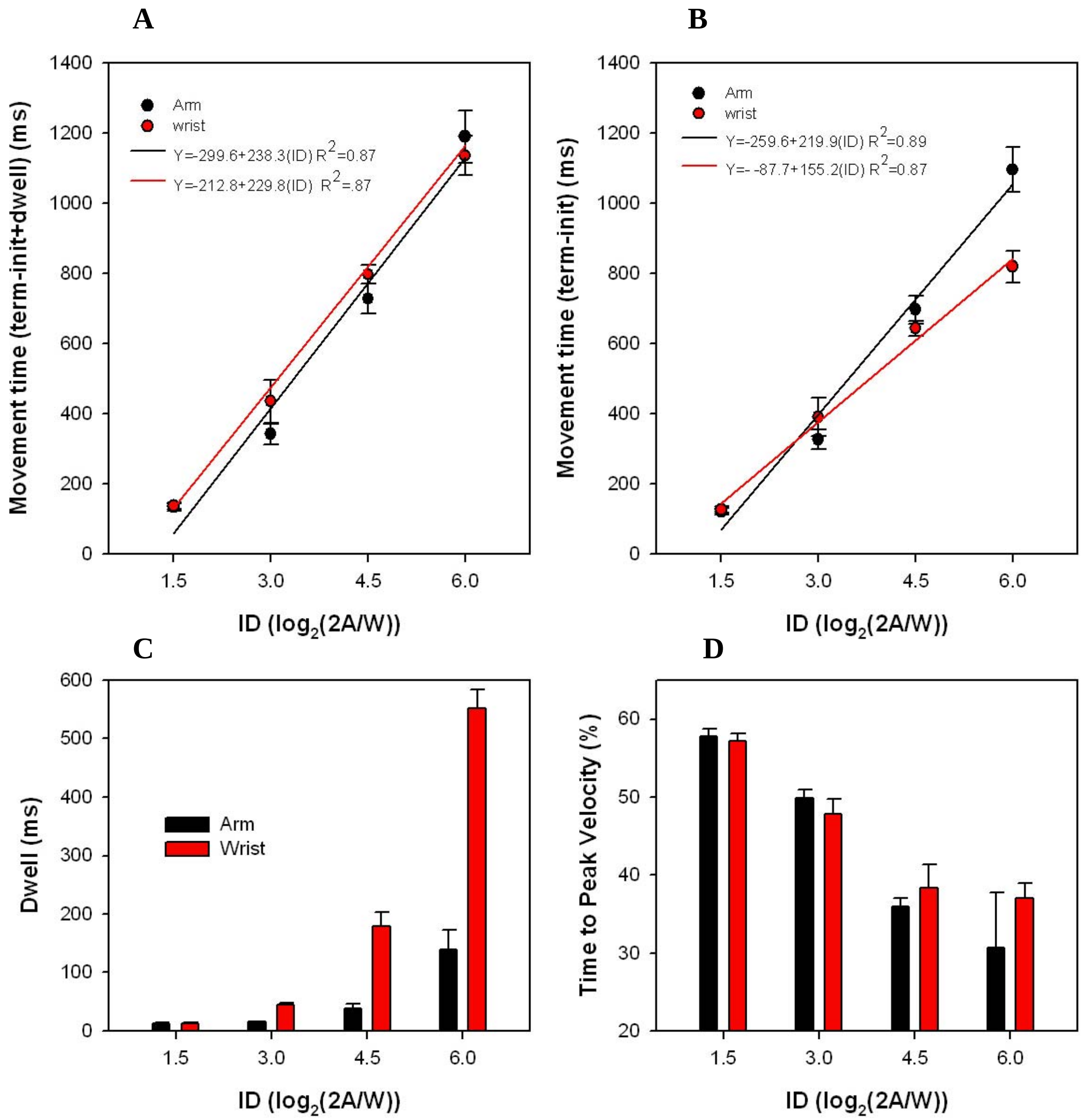

Figure 7. Mean MT1 (A), MT2 (B), dwell time (C), and percent time to peak velocity by effector (arm and wrist) and ID (D) in Experiment II. Regression lines and R^2 are provided for MT1 and MT2.

Movement time 1 (MT1)

The analysis indicated a main effect of ID, $F(3,61)=264.62$, $p<.01$. Duncan's new multiple range test indicated that MT1 increased for each ID. The main effect of effector, *F*(1,61)= 0.37, *p*>.05 and the Effector x ID interaction, *F*(3,61)= 1.61, *p*>.05, were not significant.

Movement time 2 (MT2)

The analysis indicated the main effects of the effector, *F*(1,61)= 8.42, *p*<.01, and ID, *F*(3,61) = 200.83, *p*<.01, were significant. The Effector x ID interaction, *F*(3,61)= 7.84, *p*<.01, was also significant. Simple main effects analysis failed to detect differences between effectors for IDs 1.5 and 3. The difference between effectors approached significance at ID= 4.5 (p<.10) and were different at ID= 6 with MT2 faster for the wrist movements than arm movements.

MT1 and MT2 regression analysis

The regression analyses for the arm and wrist using MT1 data indicated strong linear relationships between MT1 and ID for the arm, F(1,38)=249.64, p<.05, R^2=.87, and wrist, F(1,18)=334.1, p<.05, R^2=.91. The regression analysis for the arm and wrist using MT2 data also indicated strong linear relationships between MT2 and ID for the arm, F(1,38)=271.7, p<.05, R^2=.88, and wrist, F(1,18)=334.1, p<.05, R^2=.91. The slope of the regression line ($\beta_{1)}$ for the arm was minimally reduced from the MT1 to MT2 analysis (238.2 ms and 221.6 ms, respectively) (see Figure 8). However, β_1 for the wrist was substantially reduced from the MT1 to MT2 analysis (220.8 ms and 153.4 ms, respectively).

Dwell time

The analysis indicated main effects for the effector, *F*(3,61)=74.60, *p*<.05, and ID *F*(3,61)=63.17, *p*<.01. The Effector x ID interaction, *F*(3,61)=20.30, *p*<.05 was also significant. Simple main effects analysis failed to detect differences in dwell time between effects at IDs 1.5 and 3 but did detect differences at IDs 4.5 and 6.

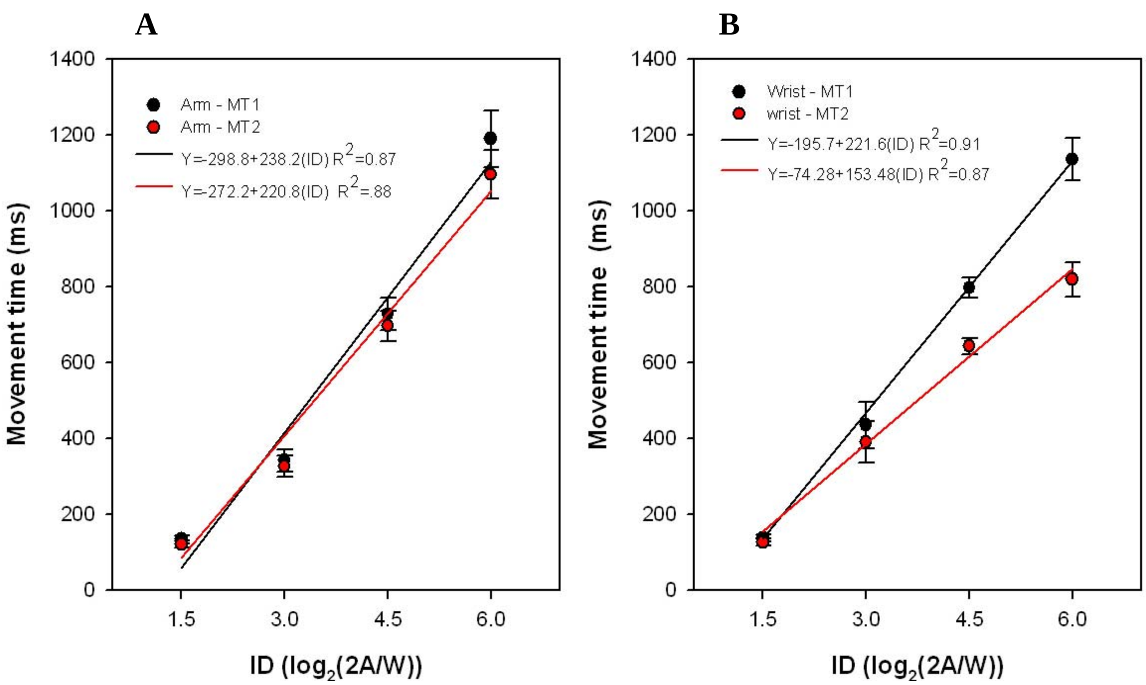

Figure 8. Mean MT1 and MT2 for the arm (A) and wrist (B). Regression lines and R^2 are provided for MT1 and MT2.

Percent time to peak velocity (%TPV)

The analysis detected a main effect ID, $F(3,61)= 88.62$, $p<.01$. The multiple range test found % TPV higher for ID=1.5 than for ID=3. In addition, % TPV was lower for IDs=4.5 and 6 which were not different from each other. The main effect of effector, $F(1,61)= 0.13$, $p>.05$, and the Effector x ID interaction, $F(3,61)= 2.04$,$p>.05$.

Discussion

Experiment II was designed to investigate if differences in movement parameters (A and W) and visual amplification of the movement information would result in differences between arm and wrist performance on Fitts' tasks. Participants in both groups were instructed to move between the targets as rapidly and accurately as they could. Amplitudes were set at 32 ^{o} for the arm, and 8 ^{o} for the wrist. Note that we doubled the amplitude for the arm from that used in Experiment I and halved the amplitude used for the wrist while keeping the IDs and the absolute visual display the same. In doing this the visual display for the small movements (A and W) used in the wrist task were amplified. Amplification of the wrist requirements and movement information was necessary to create conditions similar to that used in by Langolf et al. (1967). Note, however, that arm and wrist targets were presented with the same physical dimensions. As in Experiment I performance was measured as total movement time (MT1) and movement time minus dwell time (MT2). Results failed to detect any significant differences across effectors for MT1. Examination of velocity profiles for the wrist, however, revealed strikingly larger dwell times at the higher IDs (IDs 4.5 and 6). Analysis of MT2 revealed a significant difference in movement time across effectors at ID=6 with wrist movements having increasingly lower MT2s as ID increased. These findings are consistent with the hypothesis that previous movement studies that found effector differences may have been due to the visual amplification of the task (Langolf et al, 1976). Similarly, the finding of similar movement times for the wrist and finger in the Balakrishnan & MacKenzies (1997) study may be due to the manner in which movement time was measured. Their measure of movement time would be comparable to what we have termed MT1. However, along with visually amplifying the task, Balakrishnan & MacKenzie (1997) presented their participants with many visual cues of correct/incorrect performance. These cues, and not the visual amplification, could account for similar performance for the arm and wrist in their study. Experiment III was designed in an attempt to replicate the results of Experiment II and determine if subtle changes in visual cues influence Fitts' task.

CHAPTER V

EXPERIMENT III

Introduction

Typical Fitts tasks, whether comparing effectors or not, limit cues that inform the participants of real time performance and typically encourage percentage errors as an influence for more accurate performance. In Balakrishnan & MacKenzie's (1997) study, the cursor changed color from white to red when the participants were in the center of the target (Balakrishnan & MacKenzie, 1997). The participants may have relied on these cues and this could explain the similar performance values they conclude for the different muscles tested. In Experiments I and II, flexion/extension at the wrist/elbow was displayed as an online trace line of performance. Knowledge of performance on the previous movement may have enabled the participants to make a correction in preparation for the upcoming half cycle. Also, the harmonic nature of the wave the trace left behind, especially at ID's greater than IDc, may have aided the participants by encoding a greater rhythmic pattern of the movement. This question is examined in Experiment III by following the same criteria as Experiment II with the removal of the trace line.

Method

Participants

Participants (6 males and 3 females) between the ages of 18 and 26 yrs of age volunteered to participate in the experiment for course credit. The experimental protocol for this experiment was approved by the IRB at Texas A&M University. The participants had no prior experience with the experimental task and were not aware of the specific purpose of the study. Informed consent was obtained prior to participation in the experiment.

Apparatus

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

Procedure

Movement amplitudes and target widths were identical to those used in Experiment II. The participants moved the horizontal lever back and forth so that the cursor on the wall moved between four lines that defined the two target areas. The two targets were constructed by four blue lines creating two hollow blue rectangular shaped areas filled by a black background behind them. The cursor was visually displayed as a solid white dot that moved in and out of the targets leaving no trace of past performance. The participants performed three consecutive 15 second trials for each of the four IDs' (1.5, 3, 4.5, and 6) with the arm. After completion of the first 12 trials, the participants switched to the wrist. Participants were asked to move as fast and accurately as possible on the first two trials in preparation for the third trial labeled "the test", where participants were asked to produce their greatest level of performance. A 15 sec rest interval followed each trial. Following completion of the 12 trials, the exact program the participants completed was run again. On the next 12 trials, the participants were asked to approach each individual trial as if it were trial number 3, "the test". In the second round of trials, the trial with the lowest percentage of error was recorded as the subject's performance data.

Measures & data analysis

All data reduction followed the same criteria as Experiments I and II.

Results

Figure 9 provides mean MT1 (a), MT2 (b), dwell time (c) and %time to peak velocity (d). Both MT1 & MT2 analysis per effector is displayed in figure 10.

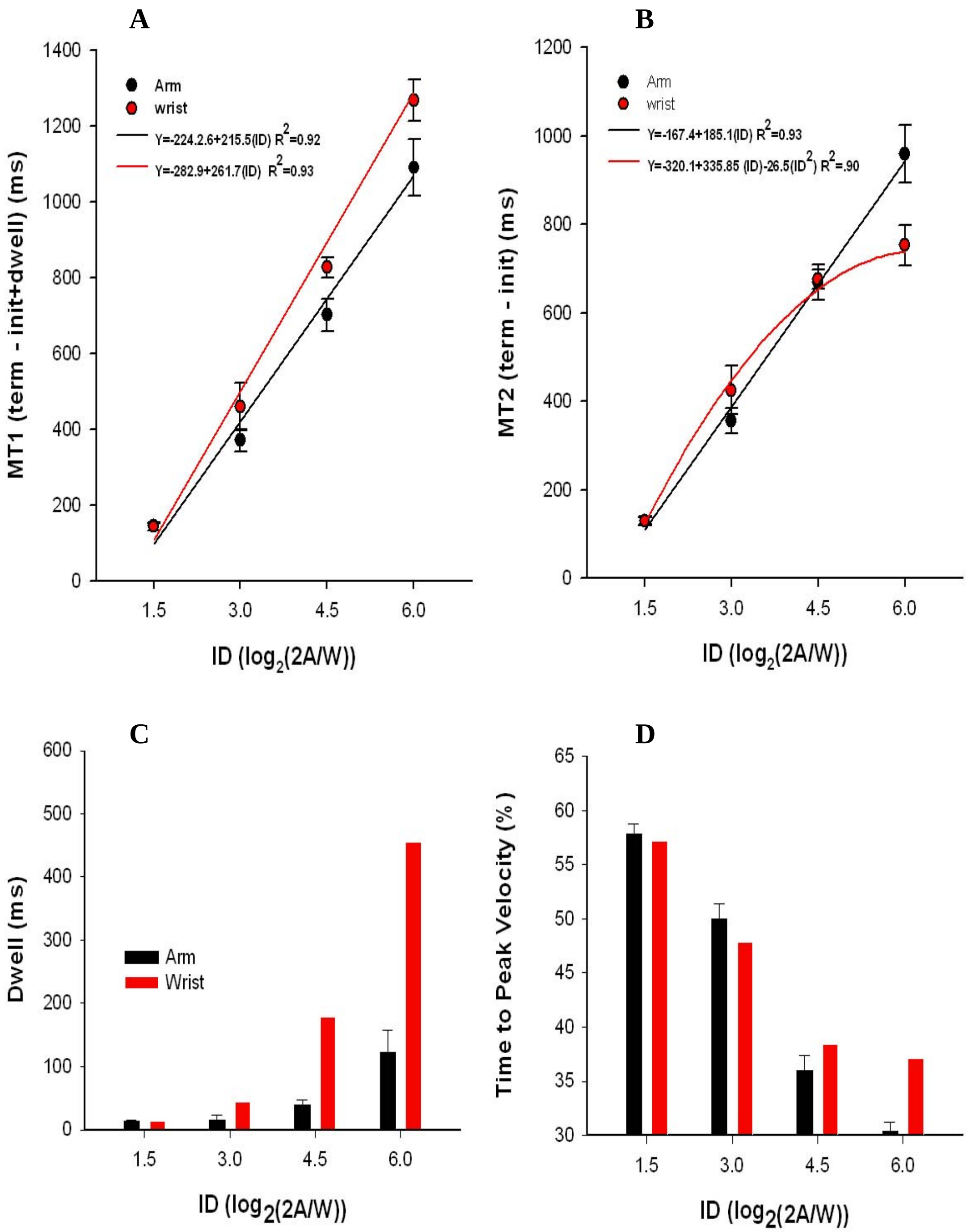

Figure 9. Mean MT1 (A), MT2 (B), dwell time (C), and percent time to peak velocity by effector (arm and wrist) and ID in (D) Experiment III. Regression lines and R^2 are provided for MT1 and MT2.

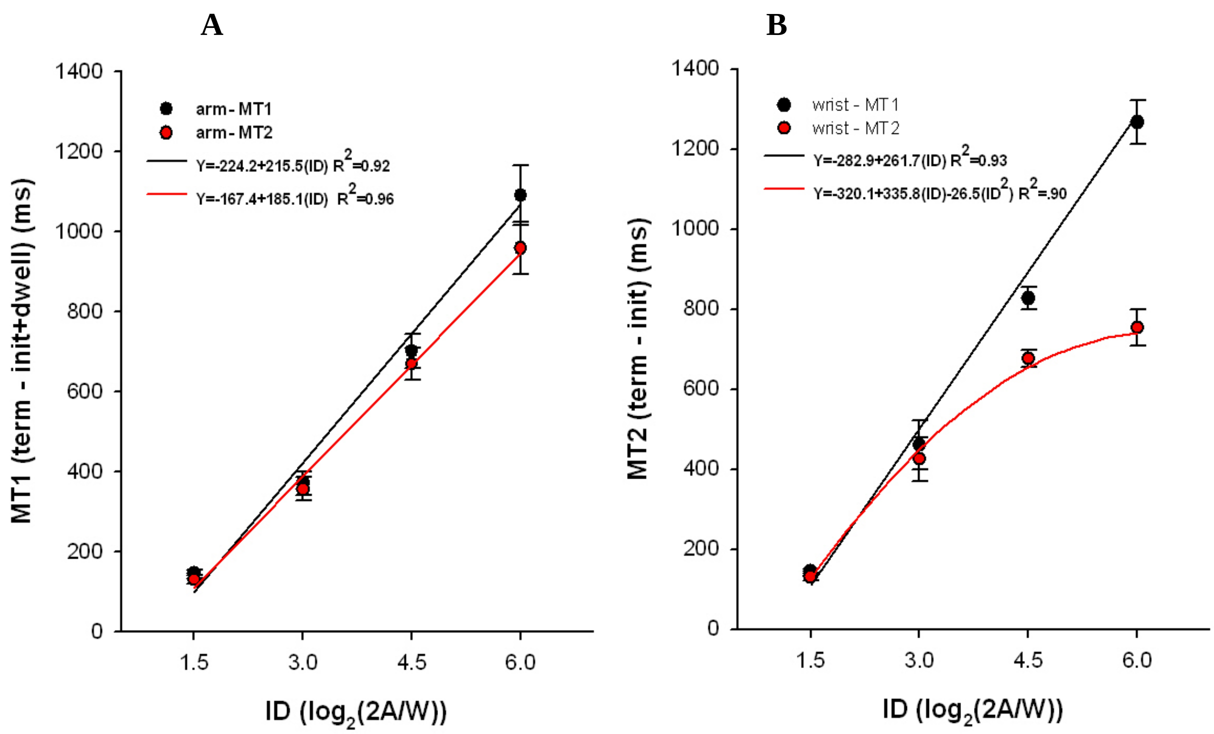

Figure 10. Mean MT1 and MT2 for the arm (A) and wrist (B) in Experiment III. Regression lines and R^2 are provided for MT1 and MT2.

Movement time 1 (MT1)

The analysis indicated main effects of the effector F(1,41)= 11.50, p<.01, and ID, F(3,41)=213.37, p<.01. Duncan's new multiple range test indicated that MT1 increased for each ID. Effector x ID interaction, F(3,41)= 2.59, p=.06, was not significant.

Movement time 2 (MT2)

The analysis indicated main effects of ID, F(3,41)= 211.95, p<.01, and Effector x ID interaction, F(3,41) = 8.98, p<.01, were significant. The main effect of Effector, F(1,41)= 3.49, p>.05, was not significant. Simple main effects analysis failed to detect differences between effectors for IDs 1.5, 3, and 4.5. The difference between effectors was significance at ID= 6 with MT2 faster for the wrist movements than arm movements.

MT1 and MT2 regression analysis

The regression analyses for the arm and wrist using MT1 data indicated strong linear relationships between MT1 and ID for the arm, $F(1,26)=256.73$, $p<.05$, $R^2=.92$, and wrist, $F(1,26)=315.24$, $p<.05$, $R^2=.94$. The regression analysis for the arm using MT2 data also indicated strong linear relationships between MT2 and ID, $F(1,26)=489.78$, $p<.05$, $R^2=.95$. However, the regression analysis for the wrist was best fit with a quadratic equation, $F(2,25)=186.96$, $p<.05$, $R^2=.93$.

Dwell time

The analysis indicated main effects for the ID $F(3,54)= 48.78$, $p<.01$, and effector, $F(1,54)= 38.19$, $p<.01$, The Effector x ID interaction, $F(3,54)=17.76$, $p>.05$ was also significant. Simple main effects analysis failed to detect differences between limbs in dwell time for IDs 1.5 and 3 but did detect significant differences for IDs 4.5 and 6.

Percent time to peak velocity (% TPV)

The analysis indicated a main effect for the ID $F(3,54)= 90.03$, $p<.01$. The main effect of effector, $F(1,54)=2.43$, $p>.05$ and the Effector x ID interaction, $F(3,54)=2.65$, $p>.05$ were not significant. Duncan's new multiple range test on ID indicated that %TPV decreased for each ID as IDs increased.

Discussion

The purpose of experiment III was to replicate the results of Experiment II and investigate if displaying the path of the movements aiding the participant's performance. Data analysis revealed performance similar to that of Experiment II. MT1 analysis revealed no significant differences in effector comparisons. MT2 analysis revealed significant differences at an ID=6 with wrist performance faster than that for the arm. Different from Experiment II was the finding that the regression analysis of MT2 resulted in a non-linear (quadratic) relationship between MT2 and ID. Note that this was not significant in Experiment II with $p=.10$. In spite of this difference the general findings show a similar pattern of results as Experiment II leading to the conclusion that the visual amplification affords the participants an advantage at the wrist regardless of how the movement is displayed (trace or cursor).

CHAPTER VI

GENERAL DISCUSSION & CONCLUSION

Fitts' law has examined in a large number of experiments over the last 50 years. One topic in the literature that has received little attention and conflicting results is the comparison of different effectors in a Fitts target task. In this manuscript three experiments were performed which were designed to provide further information on the differences in control processes and performance of arm and wrist movements in a Fitts' target task. The limited number of studies contrasting the wrist and arm movements may be due to widely accepted neurophysiology findings related to the size of motor cortex innervating muscles that control the movement of the elbow and wrist joints. Figure 11 illustrates how muscle population in the motor cortex has been shown to have disproportionate availability (Penfield & Rasmussen 1950).

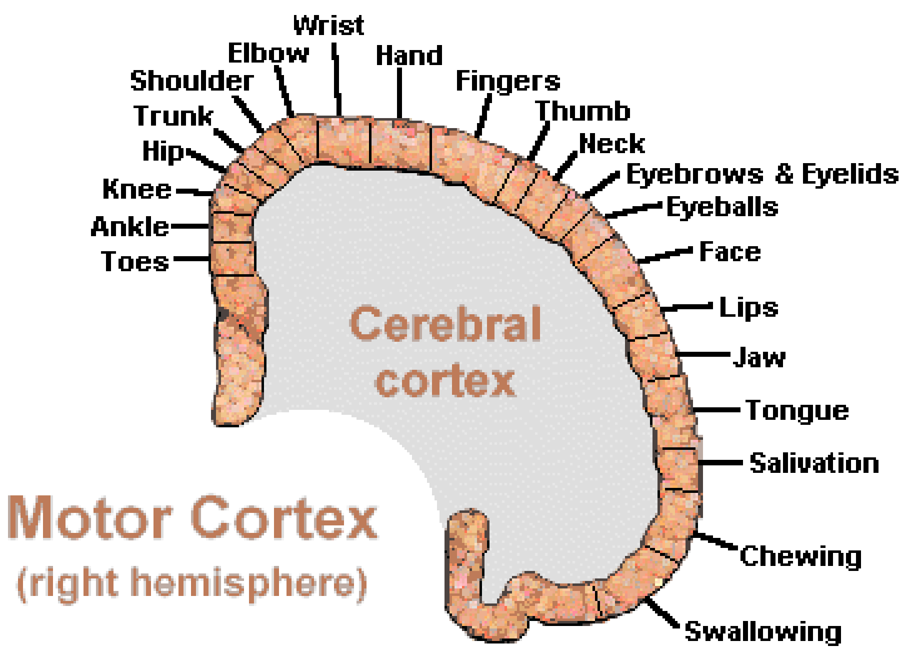

Figure 11. A representation of the relative amount of motor cortex availability per effector.

A commonly cited study by Langolf et al (1976) compared finger, wrist, and arm performance in a peg transfer and reciprocal tapping task. Their findings suggest the fingers are capable of processing a higher amount of information compared to the wrist and arm, ultimately leading to increasingly better performance of the wrist and fingers relative to the arm as the difficulty of the task increased. In line with Fitts original theory of an effector specific hierarchical system of performance, their findings also suggested the wrist is capable of greater performance than the arm (Fitts 1954, Langolf et al 1976). A study by Balakrishnan & MacKenzie (1997) refuted Langolf et al's findings and compared finger, wrist, and arm movement times in a human computer interaction Fitts' task. Their results suggest that the three effectors are capable of processing at an equal level (in bits) of performance. Recent work by Kovacs et al (2008) has shown that visual gain amplification can improve (decrease total movement time) performance in a cyclical Fitts' task at ID=6. Utilizing this finding, the present manuscript designed three experiments to investigate how this violation may be present in the conclusions of the limited literature available.

Experiment I compared performance differences between wrist and elbow flexion/extension in a cyclical target task. Participants were instructed to rapidly move a cursor in and out of two defined target areas while maintaining a high level of accuracy. Real time knowledge of performance was displayed as a trace line left behind by the cursor movement. Movement amplitude, target width, and degrees of freedom were set at an equal value between the effectors. The degrees of movement for the wrist and arm were set at 16^{o}. Target widths (1.5^{o}, 4^{o}, 1.415^{o}, .5^{o}) were used to create ID values (1.5, 3, 4.5, 6). The task consisted of two consecutive sessions. In each session, the task was designed as four blocks comprised of three trials at each ID value (1.5, 3, 4.5, 6). After completion of the first session

(12 trials), the participants were instructed to run the exact program again, only this time their movements would be recorded as their performance values. Data analysis revealed no statistical differences between either effector at any ID condition. These results follow a similar conclusion made by Balakrishnan and MacKenzie (1997) in that different effectors are capable of equal performance in a Fitts target task. However, it is important to note that even though the conclusions formed are similar to Balakrishnan and MacKenzie (1997), the performance conditions in Experiment I differed from typical investigations of this nature. In Langolf et al's (1976) study, participants performed a peg transfer task to target widths (.076, 1.07mm) set at distances (.25, 1.27cm) under a stereo microscope at power 7. Balakrishnan & MacKenzie (1997) had participants move their finger, wrist, and arm in the horizontal plane to computer visually displayed target widths of (3, 6, 12mm) set at distances of (18, 36, 72mm). Amplification of visual feedback was also increased for the wrist and even greater for the finger to counteract biomechanical differences in the joints (Balakrishnan & MacKenzie, 1997). It is interesting to note that both studies utilized visual amplification however, conclude conflicting results.

Experiment II investigated how visual amplification may influence performance differences in the wrist condition. Movement amplitude of 32 ^{o} was constant in the arm condition. Target widths (22.6 ^{o}, 8 ^{o}, 2.83 ^{o}, 1 ^{o}) were used to create ID values (1.5, 3, 4.5, 6). Movement amplitude in the wrist condition was a constant 8 ^{o}. Target widths (5.65 ^{o}, 2 ^{o}, .71 ^{o}, .25 ^{o}) created ID values (1.5, 3, 4.5, 6). The apparatus and number of trials was the same as experiment I. Similar to Balakrishnan and MacKenzie's (1997) study, the visual gain of the wrist condition was amplified to ensure the physical dimensions of the displayed task matched in both wrist and arm conditions. Data analysis revealed no statistical differences comparing wrist/arm movements to any ID value (MT1). Again, these findings are very similar to Balakrishnan and MacKenzie however; further kinematic analysis revealed dwell time of the wrist increased drastically as ID increased to 6. Removal of dwell time concluded significant differences in movement time for the wrist compared to arm (MT2). These findings agree with the notion that performance of different effectors in a Fitts target task can be influenced to show differing levels of control between effectors. A further examination in experiment III investigates how visual cues, and not the visual amplification, may have created the perceptual violation.

Experiment III investigated if online knowledge of past performance (i.e. the cursor trace line) created a perceptual aid the participants may have utilized for future movements. Participants were instructed to rapidly move a cursor in and out of two defined target areas while maintaining a high level of accuracy. The trace line from experiment I & II was removed, and only a single white dot gave a representation of limb position. The parameter constraints were kept the same as experiment II. Data analysis revealed no statistical differences comparing wrist/arm movements to any ID value (MT1). Like experiment II, dwell time increased as ID increased. Removal of dwell time revealed a significant difference in performance with the wrist having lower movement time than the arm.

The findings presented in this manuscript provide further information on performance differences of differing effectors in a Fitts' target task. The data analysis revealed that performance differences in past literature may be due to visual affordances more than motor cortex availability. This literature is not refuting that motor cortex population is disproportionate for differing effectors, it is simply pointing out that this is not the end all solution in effector comparison studies. One interesting finding was that Balakrishnan and

MacKenzie (1997) did not show differences even though the task was displayed under amplified conditions. One hypothesis is that the full kinematic analysis of the movement time was not performed, revealing a performance conclusion similar to Experiment I and II for MT1 which includes dwell time. It is reasonable to think that movements visually amplified under such small constraints would exhibit similar dwell times as MT2 analysis. The concluding findings of this study suggest that if given the same visual and physical representation of the task, the wrist and arm may utilize differing control processes, but movement performance of differing effectors can still exhibit equal levels of performance.

Future examinations of these studies might investigate if these differences in dwell time are a result of differing planning strategies between the limbs, or innate physiological differences. An investigation of reaction time between the limbs could potentially validate either claim. An analysis of reaction time would further the kinematic understanding of planning of effectors at the beginning of the movement. Also, would the visual gain amplification afford the same performance differences to the arm compared to the wrist if the constraints were reversed (i.e. gain amplified for only the arm)? According to the results found in this manuscript, a performance influence would be expected in the arm. The question would then be how the values of each effectors dwell time differ with gain amplification? A systematic scaling of increased/decreased gain amplification may establish a critical value when the visual information switches control processes, or planning strategies that maximize movement performance.

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1. Kovacs, A.J., **Boyle, J**., Gruetzmacher, N., & Shea, C.H. (2010). Coding of on-line and pre-planned movement sequences. *Acta Psychologica*, *133*,119-126.