DO ACCURACY REQUIREMENTS CHANGE BIMANUAL AND UNIMANUAL CONTROL STRATEGIES?

A Dissertation

by

CHAOYI WANG

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Chair of Committee,	Charles H. Shea
Committee Members,	John J. Buchanan
	Carl P. Gabbard
	Thomas K. Ferris
Head of Department,	Richard B. Kreider

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ABSTRACT

Bimanual coordination and unimanual aiming are two of the most studied areas in motor learning and control research. However, these areas of study have been combined in only a few experiments. By manipulating the location and the size of targets in Lissajous displays, we combined bimanual coordination tasks with Fitts' aiming tasks to form bimanual aiming in three experiments.

Experiments 1 and 2 were designed primarily to determine the degree to which the accuracy requirement influences the bimanual control processes when the Index of Difficulty (ID) was systematically increased between trials (Experiment 1) and within trials (Experiment 2) and to determine if the control strategies used to perform bimanual aiming are similar to those used in unimanual aiming. The results indicated that, as ID increased, the end-effectors' motion gradually switched from cyclical to discrete motion for both unimanual and bimanual aiming tasks. However, the transition in control strategy occurred at a lower ID for the bimanual than the unimanual aiming task. In terms of bimanual coordination, increasing the accuracy requirement/ID reduced relative phase bias between the two limbs, whereas the stability of the coupling remained similar across IDs.

Two tasks (A, B) were designed in Experiment 3 to provide performers opportunities to choose between different manual control strategies. Task A was designed so that the participants could complete the task using either unimanual or bimanual control, whereas Task B was designed so that participants could complete the task using simple or less stable bimanual coordination patterns. The purpose was to determine which control strategy the participants would choose to complete the two tasks and determine the degree to which the accuracy requirement influences the control strategy chosen. The results indicated that for both Tasks A and B at the low ID condition (ID = 2) participants preferred to use a 90° bimanual coordination pattern that is continuous, but may be more difficult from the bimanual coordination standpoint. At the high ID condition (ID = 4), the participants consistently chose to switch between more stable unimanual left and right movements in Task A and to perform a discrete 90° bimanual coordination pattern in Task B.

DEDICATION

To my Mother and Father.

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I am deeply appreciative to the chair of my committee, Dr. Charles Shea, for sharing his knowledge, experience, and wisdom during the journey of my doctoral study. I cherish his mentorship. After I graduate, I am sure I will miss the countless hours of discussion with him on interesting research ideas and findings. Moreover, if it had not been for his support and assistance, none of this would have been possible.

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Individuals regularly utilize various combinations of unimanual and bimanual coordination tasks as a part of everyday life. This occurs when driving a car, playing a musical instrument, swinging a baseball bat or golf club and even in some very routine tasks like tying one's shoes, typing on a computer or playing a video game. In many of these everyday tasks people effectively use serial combinations of unimanual and bimanual coordination patterns. This is especially evident when observing people engaged in tai chi, yoga, or dance. For example, in a tai chi movement (Louxi Aobu: Brush Knee and Step Forward), a performer has to use one arm to perform the blocking movement (brushing) while using the other arm to perform the attacking (pushing) movement. In another movement in tai chi (Dan Bian: Single Whip), a performer has to stabilize one hand in the form of a closed fist while pushing the other hand outward.

Three experiments were conducted to investigate the role of target size on the manual control strategies used to produce a variety of reciprocal unimanual and bimanual coordination tasks. In each experiment, participants were required to move between two or more targets presented in the Lissajous display. Moving between the targets in the Lissajous display requires the unimanual and/or bimanual coordination of the two limbs. The target location, size, and sequence order required may result in various unimanual and/or bimanual coordination strategies. In all three experiments, the target sizes were systematically manipulated resulting in different indexes of difficulty (e.g., ID = 3, ID = 5) for the various segments of the sequence. The primary purpose of the experiments was to determine the unimanual and/or bimanual coordination strategies that participants adopt when faced with various sequence requirements and to determine if these strategies change as accuracy requirements are increased or decreased. Given previous literature, I predicted that participants would consistently choose more stable coordination patterns over less stable coordination patterns particularly when accuracy was increased (Fontaine, Lee, & Swinnen, 1997; Haken, Kelso, & Bunz, 1985; Schoner, Haken, & Kelso, 1986; Schoner & Kelso, 1988; Zanone & Kelso, 1992). However, given the recent findings that Lissajous displays greatly reduce perceptual and attentional constraints, it would not be unexpected for less stable patterns of bimanual coordination to emerge as participants attempt to efficiently move through the target sequence.

In the following sections, I will briefly review the bimanual coordination literature. Then, I will review literature on unimanual and bimanual aiming movements (Fitts' law). Finally, I will report three experiments for my dissertation.

Bimanual Coordination

It has been repeatedly demonstrated that bimanual coordination patterns other than in-phase ($\varphi = 0°$) and anti-phase ($\varphi = 180°$) are inherently unstable and difficult to perform (Kelso, Scholz, & Schoner, 1986; Yamanishi, Kawato, & Suzuki, 1980; Zanone & Kelso, 1992), usually requiring several days of training (Fontaine et al., 1997; Lee & Swinnen, 1995; Swinnen, Dounskaia, Walter, & Serrien, 1997; Swinnen, Lee, Verschueren, Serrien, & Bogaerds, 1997). An in-phase pattern typically refers to bimanual coordination patterns where the homologous muscles of the two limbs are simultaneously activated while anti-phase pattern refers to simultaneous activation of non-homologous muscles. According to the nonlinear dynamics perspective, the difficulty in producing relative phase patterns other than in-phase and anti-phase is associated with the feature of relative phase landscape in which phase attraction draws the coupling between the limbs from less stable patterns to the more stable bimanual coordination patterns (i.e., in-phase and anti-phase patterns; e.g., Haken et al., 1985; Schoner et al., 1986; Schoner & Kelso, 1988). This bistability pattern has been modeled using nonlinear coupled limit cycle oscillators (Haken et al., 1985), perturbed by stochastic forces (Schoner et al., 1986). Yamanishi et al. (1980) and Zanone and Kelso (1992) systematically measured bimanual coordination across a variety of phase relationships. Their studies' results have verified that 0° and 180° relative phase patterns are more stable than other phase relationships and 0° is more stable than 180°.

Experimenters have demonstrated that using a 1:1 in-phase coordination pattern as a baseline, they could increase the difficulty level of bimanual coordination tasks by shifting the relative phase pattern away from 0° or 180° to other relative phase patterns such as a 90° relative phase pattern (e.g., Fontaine et al., 1997; Zanone & Kelso, 1992). This manipulation has been used to determine whether practice could alter the relative phase landscape so as to make the newly learned bimanual coordination pattern become attractive. Another method used to increase the difficulty level of a bimanual coordination task is to ask participants to perform bimanual movements with different cycling frequencies imposed on individual limbs (e.g., Summers, Davis, & Byblow,

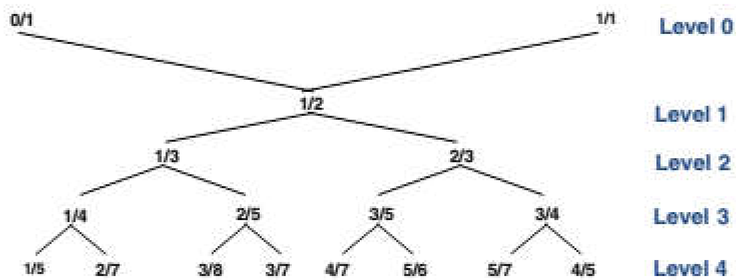

Figure 1. Farey tree illustrating a sequence of rational numbers forming successive levels of difficulty when applied to bimanual multi-frequency coordination (Boyle, Panzer, & Shea, 2012).

2002; Summers, Todd, & Kim, 1993). For example, a 1:2 frequency pattern requires participants to make one complete cycle with one limb while making two complete cycles with the other limb. This type of manipulation is particularly interesting because moving down a level in the Farey tree (Fraisse, 1946) from 1:2 to 2:3, for example, has been thought to increase the difficulty of the bimanual coordination task (see Figure 1). Similarly, the bimanual difficulty has been thought to inversely relate to the width of the resonance regions (Arnold tongue: Arnold, 1983). Higher order bimanual coordination ratios are associated with narrower resonance channels. Thus, as one moves down the level of the Farey tree or moves from the wider to narrower Arnold tongue, the multi-frequency bimanual coordination can be more easily disturbed by smaller and smaller perturbations (Treffner & Turvey, 1993).

A third way to increase the bimanual coordination difficulty involves imposing disparate movement amplitudes (e.g., Marteniuk et al., 1984; Peper et al., 1995; Ryu & Buchanan, 2004; Spijkers & Heuer, 1995) and/or disparate movement difficulty requirements for the two limbs (e.g., Kelso, Southard, & Goodman, 1979a, 1979b; Shea, Boyle, & Kovacs, 2012; Wang, Kennedy, Boyle, & Shea, 2013). When performing a bimanual task with different amplitudes, the limb producing longer movement amplitude imposing a stronger bias on the limb producing shorter amplitude, resulting in a tendency of the two limbs producing similar amplitudes. This has been termed amplitude assimilation. Amplitude assimilation has been shown in both discrete (Marteniuk et al., 1984; Sherwood, 1994) and continuous tasks (Ryu & Buchanan, 2004; Spijkers & Heuer, 1995). The difficulty of a bimanual coordination task is also increased when both movement amplitudes and target width are different resulting in different IDs. Kelso et al. (1979a, b) asked participants to make simultaneous left and right limb discrete movements to targets. When the amplitudes were different, and the target widths were different for the left and right limb movements, they found the limb producing a more difficult task affected the contralateral limb producing the easier task. The result was that participants produced similar movement times to the two tasks with the more difficult movement constraining the movement time and velocity profile of both limbs.

More recent research suggests that the difficulties in producing relative phase patterns other than in-phase and anti-phase were largely due to attentional and perceptual constraints. However, these constraints could be minimized by providing displays where salient unified information about the relationship between the two limbs was available to the performer. Lissajous feedback, for example, has been shown to provide participants' the information necessary to quickly and effectively "tune-in" a wide variety of bimanual coordination tasks (e.g., Kovacs, Buchanan, and Shea 2010a, 2010b). Lissajous feedback integrates the position of the two limbs into a single point. Often Lissajous displays are constructed where moving the right limb will result in moving the cursor left (flexion) and right (extension) and moving the left limb will result in moving the cursor up (extension) and down (flexion) in the display. A goal movement path/targets can be superimposed in the Lissajous display. The goal template can be used to guide the participants to the goal coordination pattern (e.g., in-phase, 90° relative phase, 1:2 bimanual coordination pattern) and provides a reference from which coordination errors can be easily detected and corrected. When using Lissajous displays, participants' attention is focused on a single point instead of splitting attention between the two limbs. This type of salient information allows the performer to easily detect and correct coordination errors.

As early as the 1970s, Preilowski (1972) used the Lissajous plot to study bimanual coordination in patients with partial commissurotomy and healthy control. The author required participants to move a pen on a screen recorder by rotating two connected crank handles (turning radius 6 cm) with individual arms (see Figure 2). Turning one crank will move the pen on the screen in the horizontal direction and turning the other crank will move the pen in the vertical direction. A paper with four identical linear shape tracks to be traced was attached to the surface of the screen recorder. The task was using the pen to draw a line within a narrow track (155 mm by 2.5 mm) as fast as possible without touching the sidelines (see Figure 2). The track was first presented in 16 different directions with 16 different angles requiring 16 different rotation combinations between hands. The author found that there was no difference for a particular type of movements (e.g., mirror vs. parallel, clockwise vs. counterclockwise rotation). The author also found that patients with partial commissurotomy showed less

Figure 2. Experimental apparatus and Lissajous feedback used in Preilowski (1972).

improvement after almost 500 trials of training in terms of both quality and speed compared with healthy controls.

Kovacs, Buchanan, and Shea (2009a), for example, directly tested the influence of attentional and perceptual information on the 1:1 bimanual coordination landscape. Participants were asked to produce scanning trials (0°-180° in 30° increments) with Lissajous displays and goal template. Instead of showing relative phase errors and variability at 0° is smaller than that at 180° with larger errors and variability at all other relative phase relationships, Kovacs et al. found participants could effectively produce a large range of coordination patterns after only 3 min of practice when providing perceptual information in the form of Lissajous display and goal template. That is, between 30° and 180° relative phase conditions, the relative phase errors and variability were about only 10°. For the in-phase pattern, errors and variability were about 5°.

Given the small relative phase errors and variability, it was clear that the Lissajous feedback allow the perception-action system to detect coordination errors and implement strategies to correct these errors.

In addition to the Lissajous feedback display, Mechsner et al. (2001) provided evidence that the perceptual symmetry instead of motor symmetry is the basis of coordinated bimanual movements. In their study, the authors separates the perceptual symmetry from motor symmetry in a finger oscillation task and a four-finger tapping task. For example, in the bimanual finger movement conditions, they set one palm up and the other palm down (incongruent condition) and let participants oscillate the fingers either symmetrically or in parallel. In these incongruent conditions, the symmetric mode required participants to co-activate the non-homologous muscles of the two fingers, while the parallel mode required participants to co-activate the homologous muscles. The results indicated that the bias toward the symmetric in-phase pattern was a result of perceptual and spatial constraints rather than the co-activation of homologous muscles. Mechsner et al. (2001) also demonstrated that a complex 4:3 polyrhythm could be performed relatively well when perceptual symmetry was established. Participants were asked to move two flags by turning two cranks hidden under the table. The gears for one flag was set to 1:1 ratio so that to move flag one cycle the participant had to turn the crank one cycle. The gears for the other flag were set to a 4:3 ratio so that to move the flag one cycle the participant had to turn the crank ¾ of a full cycle. Thus, to move the two flags in-phase or anti-phase, the participants has to produce 4:3 frequency ratio in the cranks. By providing this type of perceptual information, participants were able to perform the difficult 4:3 bimanual polyrhythm relatively well after 15-20 minutes of training. Mechsner et al. argued that the movements were organized in terms of perceptual goals and by providing a simple representation of perceptual goals a difficult bimanual coordination can be "spontaneously tuned in."

Franz et al. (2001) has also shown that some spatial arrangements of task display which allow for the integration of independent hand paths could stabilize bimanual in-phase coordination, while other arrangements lead to increased variability. That is, if we require participants to simultaneously move the left and right hands to draw the top and bottom halves of a circle, their two limbs performance is integrated. However, if we position the bottom half circle above the top half circle, it will be hard for the participants to integrate the two limbs motion. Franz et al. argue that a dual task can becomes a single task when the required pattern of limb movement forms an easily recognized shape (e.g., circle).

How do control processes and strategies change in unimanual and/or bimanual coordination tasks if we manipulate the accuracy requirements? In the following section, I will review the literature on Fitts' law.

Unimanual and Bimanual Aiming

Many motor skills, such as playing a piano at a fast speed, playing table tennis, require the performer to perform with speed and accuracy. We often observe a speed-accuracy trade-off phenomenon in those motor skills. Performers must tradeoff speed to increase accuracy or tradeoff accuracy to increase speed.

Before Fitts (1954) proposed a mathematic equation to quantify the speed-accuracy tradeoff relationship in a reciprocal aiming movement, researchers had already proposed several hypotheses to explain the changes in control processes related to the speed-accuracy trade-off. Most was elaborated on Woodworth's (1899) seminal work, “The Accuracy of Voluntary Movement” (see Elliott, Helsen, & Chua, 2001, for review). In Woodworth’s (1899) seminar work, the authors asked participants to draw lines with a pencil back and forth between two lines (i.e., targets). Participants were asked to reverse at the target while keeping pace with a metronome. The metronome frequency was manipulated. The results showed that the average distance of the endpoints from the target center increased as movement velocity increased. For most aiming movements, the initial portion of the movement was rapid and ballistic; as the pencil approached the target, the movement became slower, discontinuous and more variable. Woodworth proposed a two-component model of limb control. The model states that goal-directed reaching and aiming movements are composed of two distinct phases: a ballistic, preprogrammed phase (open-loop phase) that brings the limb to the vicinity of the target followed by a homing in phase (closed-loop phase). During the second phase, visual and proprioceptive feedback is used to reduce any distance between the end effector and the target position.

Fitts’ law played an important role in quantifying the speed-accuracy trade-off phenomenon. His research inspired research on the motor performance as influenced by varying difficulties. Fitts (1954) found that when participants were required to move back and forth between two target areas, a decrease in the target width (W) and/or an increase in movement amplitude (A) resulted in an increase in movement time (MT). Fitts (1954) proposed a logit equation to capture the level of difficulty, which he termed the Index of Difficulty (ID), in producing a movement. That is $ID = \log_2 (2A/W)$, where A represents the distance between the two target centers and W represents the width of the targets in the direction of the movement. Fitts noted that using this form of ID that movement time is linearly related to ID. $MT = a + b\ (ID)$ and $ID = \log_2 (2A/W)$ have come to be known as Fitts' law. Fitts' law has been tested and verified using a number of reciprocal aiming task (Annett, Golby, & Kay, 1958; Grossman, 1960; Kwon, Zelaznik, Chiu, & Pizlo, 2011; Wu, Yang, & Honda, 2010).

Several different models and hypothesis were proposed in explaining Fitts' law. Fitts (1954) original explanation was based on the Shannon and Weaver (1949) information-transmission theory. That is, movement time increases as ID increases as a result of additional bits of information to be processed to successfully achieve the target position. Crossman and Goodeve (1983) proposed an iterative-correction model. According to this model, an overall movement from an initial home position to a target region are composed of relatively open-loop phase and a closed-loop correcting phase. The open-loop phase is to initiate a movement until the closed-loop processes detected an error, then the second open-loop phase is initiated. The two phases are proposed to operate in rapid alternation until the target was approached. For longer amplitudes and/or narrower target, movement time increases because the number of corrections increases. That is, movement time increases because the performer requires more time to utilize the information available in the environment (e.g., visual, proprioceptive) to achieve the target location and plan the movement to the next target. Thus, higher ID movements required more time to process visual feedback and to make corrections than lower ID movements. However, the Crossman-Goodeve model could not account for relatively fast movements that are beyond the speed that human can process with visual feedback.

To explain the motor control process and strategy for many speed-accuracy movements that are too fast to allow for using visual feedback to make corrections, Schmidt and colleagues (1979) proposed an impulse variability hypothesis. They hypothesized that a performer constructs motor commands before movement initiation. They used the term “impulses” to describe the motor commands forwarded to the muscles, which produce the forces over a set period of time. The accuracy requirements achieved are based on the specified amount of force and time. Since movement variability relates to the exerted force and time, an increase in movement velocity results in more variable movements.

One decade later, Meyer, Abrams, Kornblum, Wright, and Smith, (1988) proposed an optimized submovement model. The model took advantage of Crossman and Goodeve’s (1983) iterative-correction model, but also incorporated Schmidt’s (1979) impulse variability hypothesis in its explanation. According to the model, in most aiming tasks, the processes involved in bringing the limb to the target can be described into two ways. The first occurs when the initial action (primary submovement) requires no correction; the other occurs when the initial impulse either undershoots or overshoots the targets, requiring a corrective impulse (secondary submovement). This process continues until the performer achieves the target location. By optimizing the control of both the primary and secondary submovements, movement accuracy is achieved in a minimum movement time.

More recently, Wolpert and colleagues (e.g., Wolpert, Ghahramani, & Flanagan, 2001; Wolpert, Ghahramani, & Jordan, 2008) have proposed an internal model or internal forward model. An internal model is a representation of sensorimotor transformation in the central nervous system (CNS). Sensorimotor transformations are bi-directional with forward model indicating the causal direction — e.g., mapping motor commands onto their sensory consequences; with inverse model indicating the opposite direction — e.g., transforming a desired sensory consequence into the motor commands. According to Wolpert et al. (2001), the CNS compares the efferent commands sent to the muscle with an efferent copy of the desired command so as to make rapid adjustments during the movement execution process. Compared to the proposed earlier models, the internal model proposed the idea that people actually initiate corrections before they made the error. The internal model also allows a performer to monitor feedback during movement execution.

A relatively number of studies also have directly measured the influence of Fitts' law on the unimanual control processes and clearly indicated that the kinematic features are different for the lower and higher IDs (e.g., Buchanan, Park, & Shea, 2004, 2006; Buchanan, 2013; Guiard, 1993, 1997; Mottet & Bootsma, 1999). The trajectories of the lower ID movements are often smooth and harmonic, with approximately the same proportion of time spent on acceleration and deceleration, and little or no dwell time occurs at movement reversal. In contrast, higher ID movements are characterized as less smooth and harmonic motion, a greater proportion of movement time spent in the deceleration phase than the acceleration phase, and longer dwell time. As the ID increased, the descriptions of the kinematic characteristics are consistent with the transition from discrete action to cyclical action (Buchanan et al., 2004, 2006; Buchanan, 2013). In a systematically scaling ID paradigm where the ID was increased or decreased within a trial, Buchanan et al. (2006) found that the repetitive aiming action can be separated by a critical ID region (ID_c) between 4.01-4.91 in a cyclical-discrete continuum. Buchanan et al. (2006) further proposed that ID = 4.5 was a critical boundary featured by increased movement variability that separate the cyclical and discrete unit of action as ID increased.

Buchanan et al. (2006) used an index of harmonicity (H) developed by Guiard, (1993, 1997). The index distinguished harmonic cyclical motion from less harmonic discrete motion. The H index is determined through the inflection points in the movement acceleration trace around the movement reversal. For example, if the movement is harmonic (cyclical motion) and no deflections are present, a single peak will occur in the acceleration trace at the movement reversal resulting an H value of 1; if the movement is inharmonic (discrete motion), the acceleration trace often crosses zero resulting an H value of 0. When smaller inflections occur in the acceleration trace, the H index is calculated as the ratio of the minimum to maximum acceleration values in the half cycle of motion. In sum, the H index ranges from 0 to 1, with smaller values representing inharmonic trajectories and larger values representing harmonic trajectories. Guiard (1997) noted that H = 0.5 represents a threshold between inharmonic and harmonic motion. The H > 0.5 indicates a more harmonic cyclical performance; the H < 0.5 indicates an inharmonic discrete performance (Guiard, 1997). Buchanan et al. based on this finding proposed a critical ID (ID_c) of 4.5 indicating the ID at which limb trajectories begin to transition from cyclical to discrete motion as ID increases or from discrete to cyclical motion as ID decreases.

Rand and colleagues also studied the influence of Fitts law on the kinematic features (e.g., movement time, peak velocity) of a two-stroke sequences (Rand, Alberts, Stelmach, & Bloedel, 1997; Rand & Stelmach, 2000). The first segment movement was an elbow extension movement away from the body and the second segment movement was either elbow extension or flexion movements (see Figure 3A). Rand et al. (1997) manipulated the ID of the second segment (ID = 3.0 and 4.83) by changing target size and movement amplitude. They wanted to examine the influence of the second segment on the movement kinematics of the first segment. The authors found that the ID of the second segment determined the kinematic features (e.g., movement time, peak velocity, time to peak velocity, and deceleration time) of the initial segment. That is, for the extension-extension sequence, when the ID of the second segment was increased the movement time for the first segment was lengthened, as indicated by an increased time to peak velocity and increased deceleration time, which parallel the changes observed in the second segment. For the extension-flexion sequence, increasing the ID of the second segment not only increased the movement time but also decreased the peak velocity for the first segment and increased intersegment interval (the time between two segments).

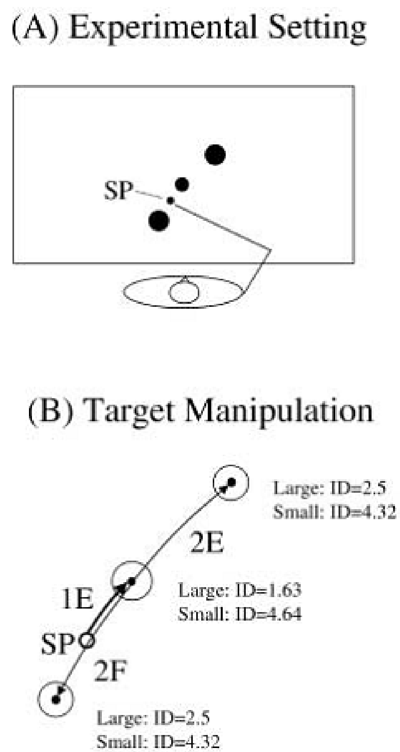

Figure 3. Illustration of the experimental setting in Rand et al. (1997) and Rand and Stelmach (2000) (A) and the ID manipulations for the first and second segments (B) in Rand and Stelmach (2000).

In addition, the movement time of the first segment in the two-segment sequences was longer than when the segment was executed alone in the control group. The authors argued that the CNS takes the features of both segments into consideration when planning and organizing the movement sequence. Specifically, the kinematic change of the first segment was related to the change of ID of the second segment, an effect labeled as “context effect” (Rosenbaum, 1991). Based on the idea of a context effect, skill acquisition is the process of transforming from concatenated individual segments into a consolidated sequence (Stelmach & Diggles, 1982).

Note that in the Rand et al. (1997) experiment the ID of the first segment was low (ID = 2.0). Thus, in Rand and Stelmach (2000) study, the ID of the first segment on the two-stroke sequences were manipulated (ID = 1.63 and 4.64) to determine whether the context-dependent effect would be diminished when the initial segment ID is high (see Figure 3B). Both the first and second segment ID was manipulated by changing the size of the targets. When the first segment was a low ID and the ID of the second segment was increased, movement time of the first element increased and the peak velocity decreased. This was found for both the extension-extension and extension-flexion sequences. However, when the ID was high for the first segment, the context-dependent effect diminished for the extension-extension sequence. That is, movement time and peak velocity for the first segment were not affected by the ID of the second segment. In contrast, for the extension-flexion sequence, as ID of the second segment increased, the movement time increased but the peak velocity did not change. Moreover, for both extension-extension and extension-flexion sequences, the intersegment interval was increased as the ID increased. The authors suggested that the ID of the first segment influenced the planning and organization of the adjacent segment in the sequence. Specifically, when the first movement segment has a high ID, the system treated nearby targets segments as distinct discrete actions.

There are a large number of studies investigated Fitts' law, however, there are limited number of literature investigated the bimanual Fitts task. Probably, this is because it is hard to do different things with two limbs. As mentioned earlier, without any perceptual manipulation, the assimilation effect between the limbs were often

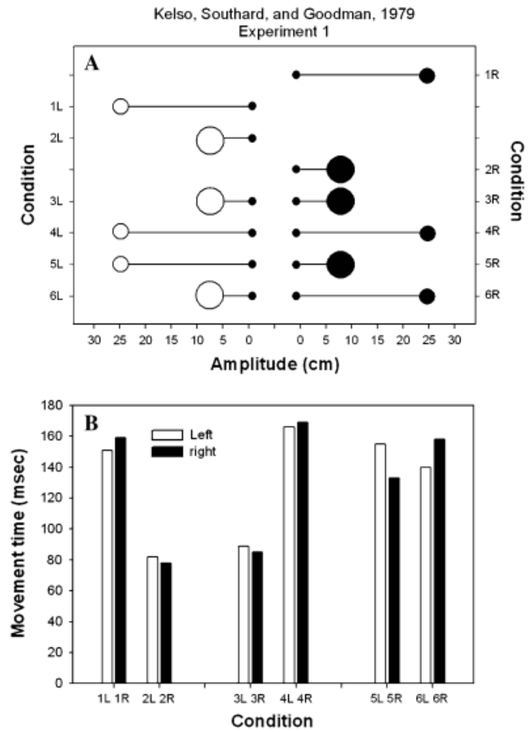

Figure 4. Illustration of the ID conditions (A) and mean movement time (B) in Kelso et al. (1979a).

observed in bimanual tasks. Kelso, Southard, and Goodman (1979a, b) found that Fitts' law was violated in discrete bimanual task (Kelso et al., 1979a, 1979b) when the requirement for one limb was different from that of the contralateral limb.

In Kelso et al. (1979a) Experiment 1, a classical bimanual discrete task experiment, participants were asked to perform a series of discrete unimanual and bimanual tasks by moving one or both index fingers from home keys located near the midline to one or two targets located left and/or right as quickly and accurately as possible. In the bimanual condition, they required participants to hit the two targets with the same ID (same amplitude and target size) or different IDs (disparate amplitude and target size). When the two movements had different IDs (see Figure 4A condition 5 and

6), the movement time for limb performing the easier movement (Figure 4B condition 5R, 6L) increased to match the movement time for the more difficult movement (Figure 4B condition 5L, 6R). The authors concluded that the limbs were constrained to act together.

Shea et al. (2012) replicated Kelso et al. (1979a) Experiment 1 using Lissajous feedback display. The critical finding was that when the two limbs were required to perform two disparate aiming tasks simultaneously, not only the movement times were similar to when the two tasks were performed separately in single-limb conditions, but the kinematic feature for each limb was also similar as when the tasks were performed separately. In the bimanual disparate ID conditions, the limb performing the easier task moved faster than the limb performing the more difficult task. Similarly, in an experiment by Wang et al. (2013), participants were asked to perform a difficult bimanual coordination pattern, which requires discrete, intermittent movement on one limb and the continuous movement of the other limb. Using Lissajous feedback and a goal template, participants were able to perform this difficult bimanual coordination task with only 10 minutes of practice (see Figure 5). The authors conclude that people can overcome the intrinsic difficulties associated with performing difficult bimanual coordination pattern with provided appropriate perceptual information/feedback. These results again provided evidence of the power of visual display on overcoming the difficulties associated with bimanual discrete tasks.

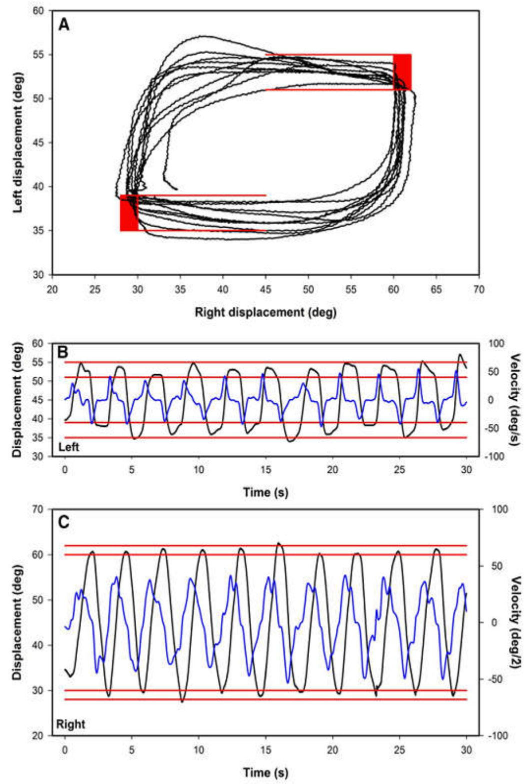

Figure 5. Illustration of the Lissajous plot (A), left (B) and right (C) displacements (*black*) and velocities (*blue*) for the test trial for a typical participant in Wang et al. (2013).

In addition to movement time, Franz and McCormick (2010) measured reaction time in discrete bimanual reaching tasks with disparate IDs. The reaction time was lower when the two limbs moving to targets with the same ID (congruent condition) than when the two limbs move to targets with different IDs (incongruent condition) (see Figure 6). Interestingly, the reaction times in the incongruent condition were reduced when the two targets were connected with a line in the display (Exp. 1). The reaction times were also reduced when the language used in the instructions unified the two actions into a single plan (Exp. 2, separate instruction vs. unified instruction). In other words, tasks that may be initially perceived as a dual task can be perceived as a single task when the visual

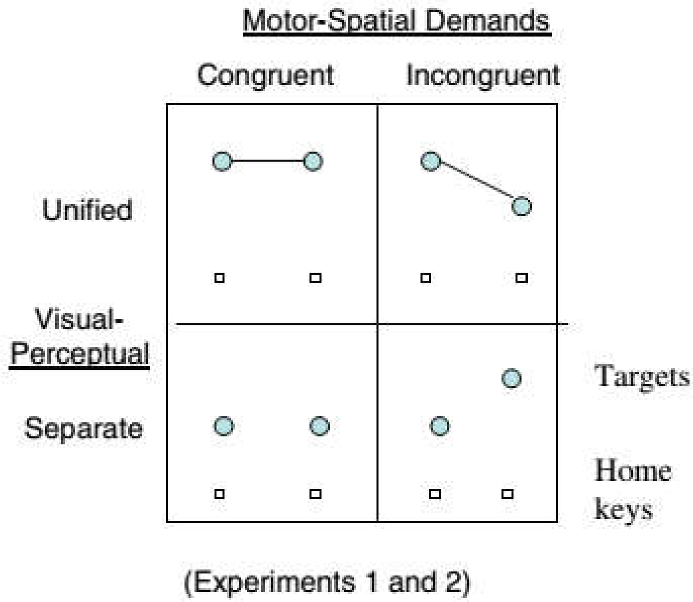

Figure 6. Illustration of the visual-perceptual conditions (separate vs. unified) and the target distance (congruent vs. incongruent) in Franz and McCormick (2010).

display or the language used integrate the two tasks into a unified representation. Thus, conceptually unifying a task representation may also help the performer to reduce lower level sensorimotor constraints.

Summary

Bimanual coordination, such as slicing a bread, opening a bottle, and tying shoe laces are important to our daily life. However, some bimanual tasks have been demonstrated to be very difficult to perform unless salient, integrated feedback is provided. Lissajous display has been shown to be an efficient way to facilitate the performance of both continuous/reciprocal bimanual coordination tasks and discrete bimanual tasks. Previous studies have examined discrete bimanual Fitts' tasks using

Lissajous feedback display, but studies on bimanual Fitts task using enhanced display is limited (Shea et al., 2012; Wang et al., 2013).

By manipulating the location and the size of targets in Lissajous displays, we combined the bimanual coordination and Fitts' law literature and proposed three experiments to examine whether accuracy requirements change bimanual and unimanual control strategies. Experiment 1 and 2 systematically examined the bimanual and unimanual control strategies of unimanual and bimanual aiming when the accuracy requirements were systematically manipulated between trials (Experiment 1) and within a trial (Experiment 2). Experiment 3 provided participants opportunities to choose between different unimanual and bimanual control strategies or to choose between more stable and less stable bimanual control strategies. It is important to understand how accuracy requirements change bimanual and unimanual control strategies. The results of this study will add to the diverse population of studies that examine how movement difficulty influences bimanual and unimanual control strategies.

Throughout this dissertation, the term "control strategy" will be used to describe if the displacement trace of an aiming movement is cyclical or discrete. The cyclical and discrete kinematic features (e.g., harmonicity, percent time to peak velocity) in Fitts' aiming literature are consistent with the description of open-loop and closed-loop control processes. The term "bimanual control strategy" will be used to describe the coordination pattern of two hands working together, such as in-phase, 90° relative phase, 1:2 bimanual coordination patterns (Kelso, 1995).

CHAPTER II

EXPERIMENT 1: TARGET WIDTH SCALING IN UNIMANUAL AND BIMANUAL AIMING TASKS

Introduction

Experiment 1 investigated unimanual and bimanual reciprocal aiming tasks with a fixed amplitude and target sizes that created IDs of 3, 4, 5, and 6. The primary purpose of Experiment 1 was to extend previous discrete bimanual aiming research (e.g., Kelso et al., 1979a, 1979b; Shea et al., 2012) to reciprocal bimanual tasks in order to determine the degree to which the difficulty of the movement influences the bimanual control processes and to determine if the control strategies used to perform bimanual aiming tasks are similar to those used in unimanual right-limb aiming tasks (Buchanan et al., 2006; Guiard, 1993, 1997). The second purpose was to determine whether the influence of accuracy requirement changes on control strategies' change for the right-limb aiming tasks can be extended to the left-limb aiming tasks. Note that the majority of aiming research has used dominant limb performance. To my knowledge, the current study is the first study that investigates bimanual aiming movements using continuous bimanual coordination measurements (i.e., relative phase, relative phase variability). The last purpose was to determine whether the order of presenting ID (i.e., increasing or decreasing ID order) influence the control strategies utilized in bimanual and unimanual aiming tasks.

In both the unimanual and bimanual conditions, I predict that movement in the ID3 condition to be cyclical with end-effectors' motion consistent with an open-loop control description. In the ID6 condition I expect the end-effectors' motion to be discrete which is consistent with a more closed-loop control description. This will be reflected in the movement kinematics (e.g., harmonicity, deceleration time). Given previous literature of the impact of movement ID on single limb's performance (e.g., Boyle & Shea, 2011; Boyle, Kennedy, & Shea, 2012; Buchanan et al., 2006; Guiard, 1993, 1997; Kelso et al., 1979a, 1979b), I predict that in the lower ID condition, shorter movement times, shorter dwell times, relatively high percent time (≈ 50%) to peak velocity, and higher H values for both limbs will be observed compared to higher ID conditions with longer movement times, increased dwell times, smaller percent time to peak velocity, and lower H values for both limbs will be observed. I also expect the cycle duration for the unimanual conditions will be shorter than that for the bimanual conditions in the high ID conditions but that this difference will diminish as the ID is decreased. This prediction is based on the idea that, for unimanual and bimanual tasks with the same ID, greater processing demands are required in the bimanual conditions than in the unimanual condition (Kelso et al., 1979a, 1979b; Shea et al., 2012; Wang et al., 2013). As the ID is increased (target size decreased) in the bimanual condition, the participants need to more tightly couple the two limbs. This should be reflected in decreased relative phase bias while maintain the same relative phase variability. In addition, based on Buchanan et al. (2006) finding that, "the limb's motion underwent a loss of stability as the ID_c region was approached", I predict that harmonicity variability will be observed in

ID = 4 or ID = 5 condition because the two ID conditions are near the ID_c value of 4.5, established by Buchanan et al. (2006). Lastly, participants may attempt to maintain a particular control strategy as the ID is increased or decreased, thus I predict different transition patterns between the increasing and decreasing ID order conditions.

Methods

Participants

Twenty-four Texas A&M college student participants were recruited for Experiment 1. Participants with prior experience with the experimental task were excluded. Participants signed the consent form before entering the test room. A modified Coren handedness evaluation (Coren, 1993) was used to document the participants' handedness. All participants were classified as right-arm dominant.

Apparatus

The apparatus consists of two horizontal levers affixed at one end to a near-frictionless vertical axle (see Figure 7). One lever was positioned on the left side of a table and was used by the left limb and the other on the right side was used by the right limb. The axles, which rotated freely in ball bearing supports, allowed the levers to move in the horizontal plane over the table surface. Near the distal end of the levers, vertical handles were attached. The positions of the handles were adjusted so that when the participants rested their forearms on the levers with their elbows aligned over the axis of rotation they could comfortably grasp the handles (palms facing each other). The horizontal movements of the levers were monitored (200 Hz) by potentiometers that

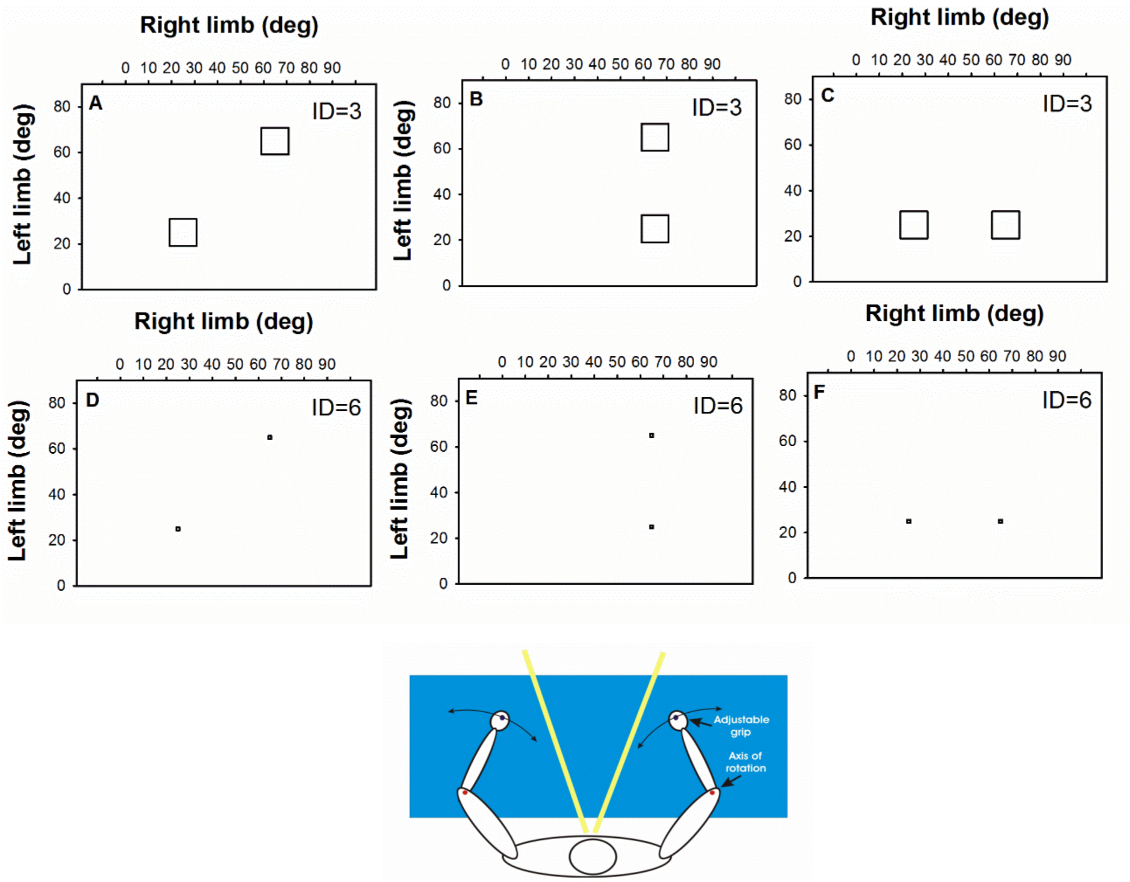

Figure 7. The experimental setup and feedback displays for the bimanual (A: ID3, D: ID6), unimanual left (B: ID3, E: ID6) and unimanual right (C: ID3, F: ID6) conditions in Experiment 1.

were attached to the axles. The online data were used to move the cursor in the Lissajous display and were stored for later analysis. The cursor indicating the current position of the lever(s) was projected on the wall 2 m in front of the participant by a projection system mounted above and behind the table. A wooden frame was used to block participants' vision of their limbs.

Procedure

Participants were seated in a height adjustable chair in front of the table on which the levers were mounted. In each condition two target boxes were projected on the wall directly in front of them (see Figure 7). Participants were asked to move the cursor as quickly and accurately as possible between the two targets. Participants were told that they should reverse within the target area. The horizontal/vertical distance/amplitude between the targets was set at 40°. The width of the two targets in the direction of movement was set to 10°, 5°, 2.5°, and 1.25° to create IDs of 3, 4, 5, and 6 conditions according to Fitts' Law: $ID = \log_2(2A/W)$ (Fitts, 1954).

The position of the targets created bimanual and unimanual conditions for each ID. In the bimanual condition the participant was required to use both arms to perform the task while in the unimanual condition the movement of only one arm was required. Note that in the Lissajous display left limb movement moved the cursor up (extension) and down (flexion) while movement of the right limb moved the cursor left (flexion) and right (extension). In the bimanual conditions the position of the two targets required participants to produce an in-phase movement (flexing and extending both arms with the same angles) (see Figure 7A, D). In the unimanual conditions, participants only needed to move one arm to move between the targets (see Figure 7B, C, E, F). Each participant was assigned to either a bimanual or unimanual condition.

Each bimanual/unimanual condition included two orders (increasing or decreasing ID). In the increasing bimanual order, participants practiced 2 trials with each bimanual task in the order of ID3, ID4, ID5, and ID6 (8 total trials); in the decreasing bimanual order, participants practiced 2 trials with each bimanual task in the order of ID6, ID5, ID4, and ID3 (8 total trials). The two orders were counterbalanced. In unimanual condition, participants used their left limb to control the cursor in one condition. In the other unimanual condition participants used their right limb to control the cursor. Both unimanual conditions involved 8 trials of ID3, ID4, ID5, and ID6 (2 trials for each ID present in the increasing ID order) and 8 trials of ID6, ID5, ID4, and ID3 (2 trials for each ID present in the decreasing ID order) tasks. The two orders and the order of the limbs were counterbalanced. Each trial lasts 30 seconds.

Data analysis

Trials 2, 4, 6, and 8 (IDs = 3, 4, 5, 6 or IDs = 6, 5, 4, 3) were subjected to data analysis. Data analyses were performed using Matlab (Mathworks, Natick, MA). The individual trial time series were used to compute lever displacement, velocity and acceleration. A three-point difference algorithm was used to compute the velocity and acceleration. To reduce noise, the angular displacement, velocity and acceleration time series were filtered with a second-order dual-pass Butterworth filter with a cut-off frequency of 10 Hz. The analyses presented will focus on both the unimanual performance of the left and right limbs and bimanual coordination performance of the required in-phase patterns.

Unimanual measurements. Cycle durations (CD) and cycle duration variability (CDV) were computed on a half cycle basis with each cycle representing every zero crossing (Z_{Ci} and Z_{Ci+1}) in the mean centered displacement trace (CD = (Z_{Ci+1}-Z_{Ci})*1/sample frequency). CDV was defined as the standard deviation of the cycle durations across a trial. CD and CDV provide information on the overall speed and stability of each moving limb.

After finding the peak velocity (PV) for each half cycle, movement onset and offset were determined to calculate movement time (MT), dwell time (DT), percent time to peak velocity (PTPV) for each limb. MT, DT, and PTPV were calculated on a half-cycle basis with each half cycle representing an extension or flexion movement. Movement onset was calculated by tracking backward from PV to a value of 5% of PV. Movement offset was calculated by tracing forward from PV to a value of 5% of PV. In a reciprocal aiming task, as ID increases the time spent on reversing the movement in preparation for the following cycle increases (Boyle & Shea, 2011; Kovacs, Buchanan, & Shea, 2008). This time is known as dwell time, DT = movement $onset_{i+1}$ – movement $offset_i$. Movement time was calculated by the equation MT = movement $offset_i$ – movement $onset_i$. Total time (TT) across a trial which was calculated by the equation TT = DT + MT results in almost the same value as the cycle duration across a trial, thus in this dissertation the concept of total time and the concept of cycle duration were interchangeable. The percent time to peak velocity was determined by the equation, PTPV = $(PV_i – onset_i)/(offset_i – onset_i)$.

Windows between adjacent pairs of zero crossings in the displacement trace were defined in order to compute an index of movement harmonicity (H; Guiard 1993) and a harmonicity variability (SD of H; Buchanan et al., 2006). Each time window comprised a single movement reversal. Within each time window, all the deflections of the filtered acceleration trace were identified. When the deflections are all positive or negative within the calculation window, H was computed as the ratio of absolute minimum to absolute maximum acceleration. When a single peak (sinusoidal acceleration) occurred in the acceleration trace within the calculation window, the value of H was 1, indicating a harmonic motion of the limb. If the acceleration trace crossed from negative to positive (or vice versa) within the window, the value of H was 0, indicating inharmonic motion. Finally, the individual harmonicity values for each time window within a trial were averaged yielding a global estimate of H for that participant and trial. Harmonicity variability was defined as the standard deviation of the H values across a trial. The mean H values will be analyzed to identify the transition from cyclical to discrete motions (and vice versa) based on the demarcation value of H = 0.5 (Buchanan et al., 2006; Guiard, 1997). The SD of H will be analyzed to identify enhancement of fluctuations as a function of ID.

Bimanual measurements. For each trial in the bimanual condition, a continuous relative phase measure (ϕ_c) was computed to examine the spatiotemporal coordination of the limbs during the task. To calculate the continuous relative phase, first, the continuous phase angle (θ) was computed from the lever displacement (x) and velocity ($\dot{x}$) time series of each limb. The x and $\dot{x}$ time series were mean centered and rescaled to the range -1 to 1. A continuous phase angle (θ) for each limb (LA, RA) was computed for each sampled point (i) as follows (Kelso et al., 1986):

$$\theta_i = tan^{-1}(\dot{x}_i / x_i).$$

Then the continuous phase angle for the left limb was subtracted from the right limb for each sampled point: $RP_i = \theta_{LAi}$-θ_{RAi}. The difference between the two limbs' continuous relative phase values were averaged across a trial. Relative phase variability (SD of RP) was computed as the standard deviation of the signed relative phase over a trial, and this provides an estimate of the stability of bimanual coordination. The mean RP and its variability together provide a measure of coupling of the limbs, with a smaller relative phase (RP) value indicating a reduced relative phase bias between the two limbs while relative phase variability remained at the same level.

The RP and SD of RP will be analyzed in an ID (3, 4, 5, 6) × Order (increasing, decreasing IDs) analysis of variance (ANOVA) with repeated measure on both factors. The cycle duration, cycle duration variability, MT, DT, PTPV, H values, and SD of H data will be analyzed in a Manual (bimanual, unimanual) × ID (3, 4, 5, 6) × Limb (left, right) × Order (increasing, decreasing IDs) analysis of variance (ANOVA) with repeated measures on ID, Limb, and Order. Significant main effects will be further analyzed with Duncan's new multiple range test and significant interactions will be further analyzed with simple main effects. An alpha level of .05 will be used for all tests.

Results

Lissajous plot and displacements for the lowest ID3 and the highest ID6 condition for a participant in the bimanual, unimanual left and right conditions are provided in Figure 8. The descriptive statistics for bimanual and unimanual measures at different IDs and limbs are provided in Table 1.

Unimanual performance

Cycle duration. The analysis of cycle duration detected a main effect of ID, $F(3, 42) = 278.22$, $p < .01$. In addition, the Manual × ID interaction, $F(3, 42) = 6.00$, $p < .01$,

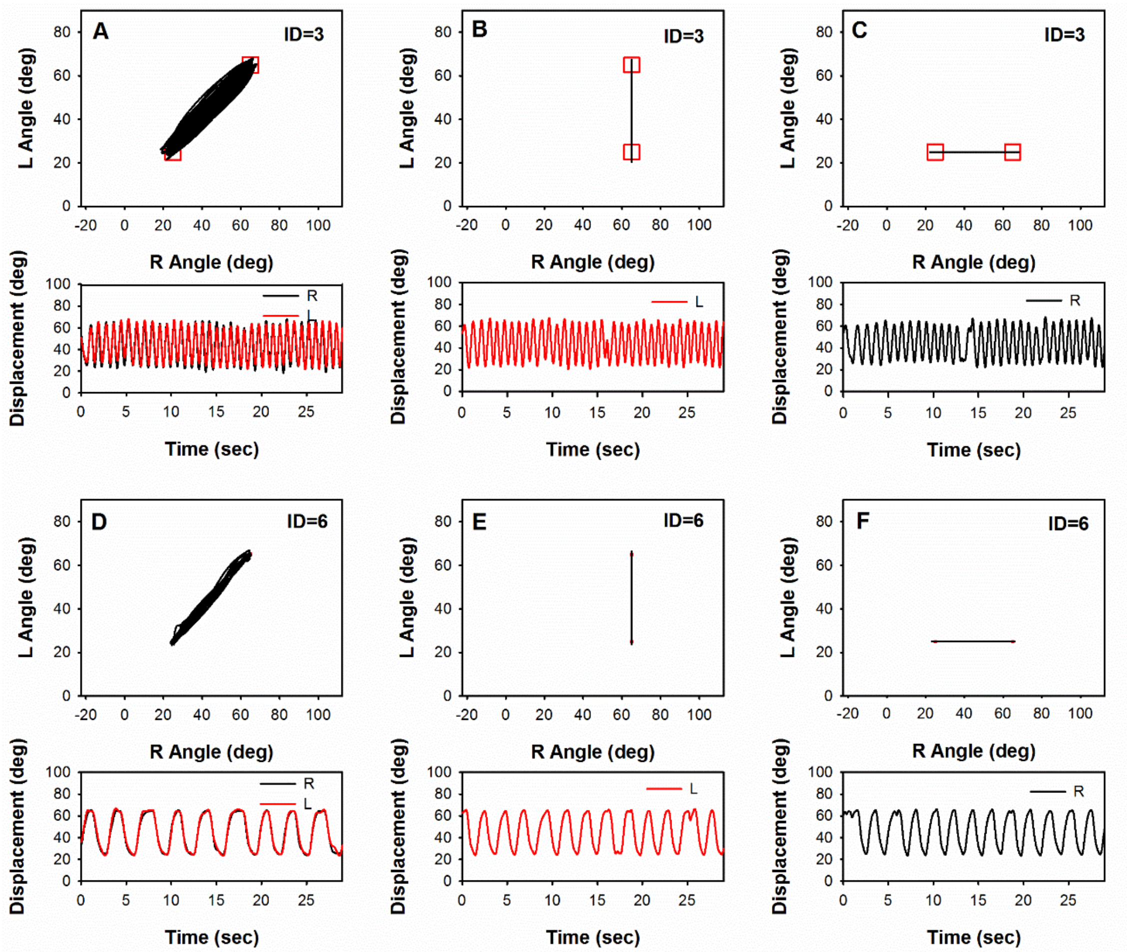

Figure 8. Lissajous plot and displacement at ID3 (A-C) and ID6 (D-F) for a participant in the bimanual (A,D), unimanual left (B,E) and right (C,F) conditions. L and R represent the left and right limbs respectively.

and the Order × ID interaction, $F(3, 42) = 3.15$, $p < .05$, were significant (see Figure 9A,B). Simple main effect analysis of the Manual × ID interaction indicated that cycle duration increased as ID increased for both the bimanual and unimanual conditions. Simple main effect analysis of the Manual × ID interaction also indicated that the cycle duration was longer for the bimanual than the unimanual condition at ID6 (bimanual M = 1.33s, SE = .046s: unimanual M = 1.13s, SE = .030s), but no differences were detected at IDs3-5. The symbols of *M* and *SE* represent mean and standard error values, respectively. Simple main effect analysis of the Order × ID interaction indicated that cycle duration increased as ID increased for both the increasing and decreasing ID orders. Simple main effect analysis of the Order × ID interaction also indicated that the cycle duration was longer for the decreasing ID order than the increasing ID order at ID6 (increasing $M = 1.18$s, $SE = .036$s: decreasing $M = 1.26$s, $SE = .047$s), but no differences in cycle duration were detected at IDs3-5. No other main effects or interactions were significant.

Cycle duration variability. The analysis of cycle duration variability detected a main effect of ID, $F(3, 42) = 129.40, p < .01$. In addition, the Manual × ID interaction, $F(3, 42) = 5.95, p < .01$, was significant (see Figure 9C). Simple main effect analysis of the Manual × ID interaction for both the bimanual and unimanual conditions failed to indicate a difference in cycle duration variability between ID3 and ID4 but indicated that cycle duration variability increased from IDs4-6 as ID increased. Simple main effect analysis of the Manual × ID interaction also indicated that the cycle duration variability was larger for the bimanual than the unimanual condition at ID6 (bimanual $M = .23$s, $SE = .012$s: unimanual $M = .17$s, $SE = .009$s) but no differences were detected at IDs3-5. No other main effects or interactions were significant.

Movement time. The analysis of movement time detected a main effect of ID, $F(3, 42) = 183.21, p < .01$. In addition, the Order × ID interaction, $F(3, 42) = 3.63, p < .05$, was significant (see Figure 9D). Simple main effect analysis of the Order × ID interaction indicated that movement time increased as ID increased for both the increasing and decreasing ID order. Simple main effect analysis of the Order × ID also indicated that the movement time was longer for the bimanual than the unimanual condition at ID6 (increasing $M = .96$s, $SE = .032$s: decreasing $M = 1.06$s, $SE = .033$s) but no difference between the two orders was detected at IDs3-5. No other main effects or interactions were significant.

Dwell time. The analysis of dwell time detected a main effect of Manual, $F(1, 14) = 8.68$, $p < .05$, Limb, $F(1, 14) = 5.33$, $p < .05$, and ID, $F(3, 42) = 62.61$, $p < .01$. In addition, the Manual × ID interaction, $F(3, 42) = 10.06$, $p < .01$, was significant (see Figure 9E). The dwell time for the left limb ($M = .075$s, $SE = .010$s) was slightly shorter than the right limb ($M = .083$s, $SE = .010$s). Simple main effect analysis of the Manual × ID interaction for the bimanual condition failed to indicate a difference in dwell time between ID3 and ID4, but indicated that the dwell time become longer as ID increased from IDs4-6, however, the analysis for the unimanual condition detected that the difference in dwell time between ID3 and ID4 and the difference in dwell time between ID4 and ID5 were not significant but the dwell time increased from ID5 to ID6. Simple main effect analysis of the Manual × ID interaction indicated that the dwell time was longer for the bimanual than the unimanual condition at ID6 (bimanual $M = .29$s, $SE = .022$s: unimanual $M = .13$s, $SE = .017$s), but no difference in dwell time between the bimanual and unimanual conditions was detected at the IDs3-5. No other main effects or interactions were significant.

Table 1 Bimanual and unimanual descriptive statistics in Experiment 1**.**

	Bimanual condition				Unimanual condition			
	ID = 3	ID = 4	ID = 5	ID = 6	ID = 3	ID = 4	ID = 5	ID = 6
	M	*M*	*M*	*M*	*M*	*M*	*M*	*M*
CD (*s*) L *	0.519	0.744	1.050	1.512	0.435	0.611	0.870	1.123
CD (*s*) R *	0.519	0.755	1.052	1.513	0.456	0.644	0.915	1.143
CDV (*s*) L	0.091	0.149	0.229	0.393	0.057	0.100	0.156	0.186
CDV (*s*) R	0.097	0.162	0.220	0.388	0.055	0.109	0.166	0.215
MT (*s*) L	0.498	0.700	0.992	1.371	0.418	0.585	0.825	1.045
MT (*s*) R	0.497	0.718	0.959	1.280	0.438	0.614	0.866	1.055
DT (*s*) L	0.021	0.033	0.056	0.146	0.018	0.025	0.043	0.077
DT (*s*) R	0.023	0.037	0.095	0.243	0.019	0.028	0.048	0.083
PTPV (%) L	45.40	37.06	33.28	31.36	48.90	44.91	38.67	33.90
PTPV (%) R	44.59	36.70	31.14	30.12	48.35	43.76	36.11	33.38
Harmonicity L	0.82	0.44	0.15	0.04	0.94	0.74	0.29	0.08
Harmonicity R	0.78	0.35	0.11	0.02	0.91	0.69	0.26	0.09
SD of H L	0.24	0.30	0.15	0.05	0.14	0.29	0.27	0.12
SD of H R	0.25	0.26	0.12	0.04	0.15	0.27	0.26	0.14
RP (*deg*)	6.78	4.52	2.85	2.00				
SD of RP (*deg*)	9.19	9.64	8.82	9.50				

Note. M-mean, L-left, R-right, CD-cycle duration, CDV-cycle duration variability, MT-movement time, DT-dwell time, PTPV-percent time to peak velocity, H-harmonicity, SD of H-standard deviation of harmonicity, RP-relative phase, SD of RP-standard deviation of relative phase. * In this dissertation, the concept of CD and the concept of Total Time (TT), which was calculated by the equation TT = DT + MT, were interchangeable.

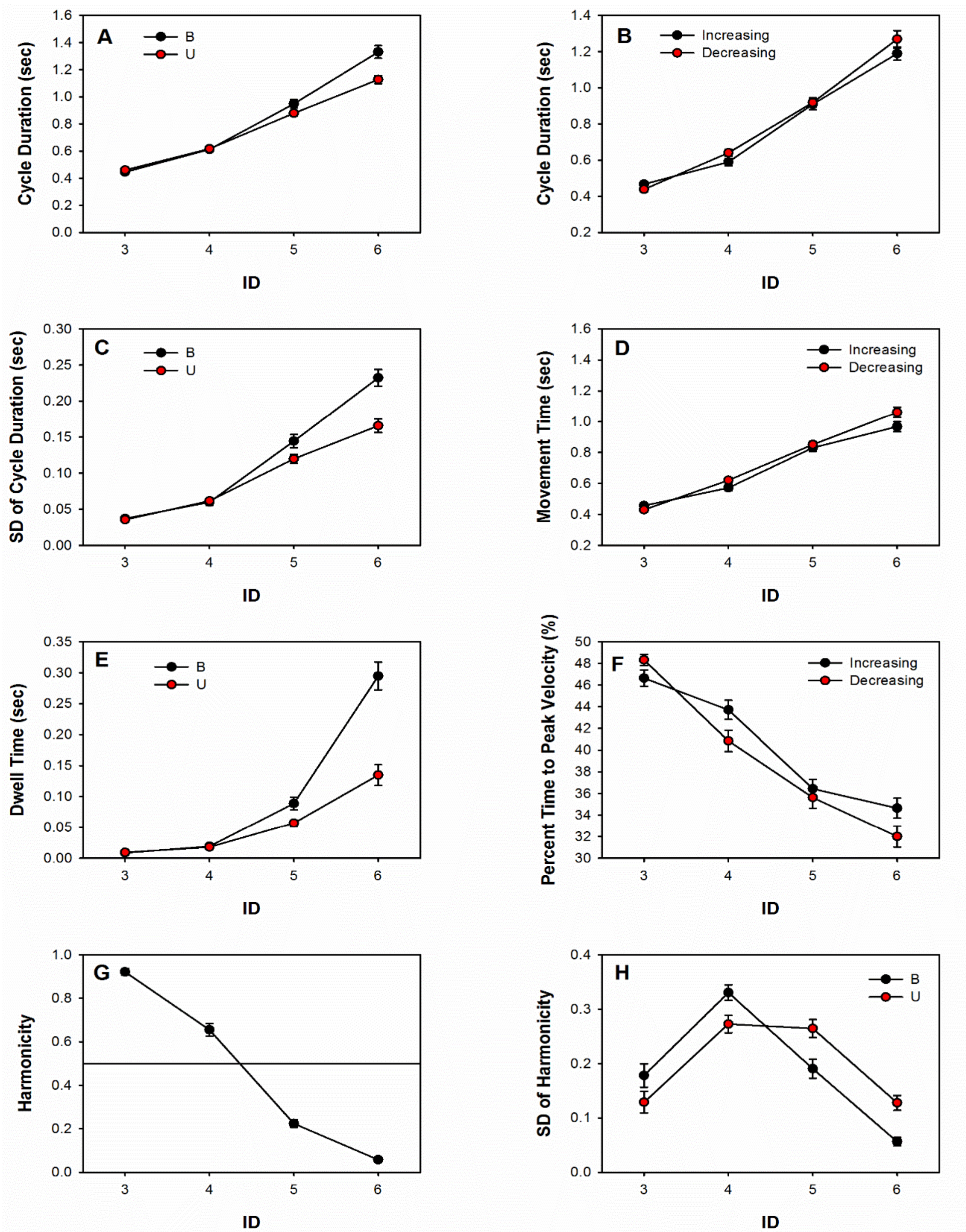

Figure 9. Mean cycle duration (A, B), cycle duration variability (C), movement time (D), dwell time (E), percent time to peak velocity (F), harmonicity (G), harmonicity variability (H) for the bimanual ("B") and unimanual ("U") conditions or the increasing and decreasing ID orders as a function of ID. The error bars represent standard error.

Percent time to peak velocity. The analysis of percent time to peak velocity detected a main effect of ID, $F(3, 42) = 77.44$, $p < .01$. In addition, the Order × ID interaction, $F(3, 14) = 5.63$, $p < .01$, was significant (see Figure 9F). Simple main effect analysis of the Order × ID interaction indicated that for the increasing ID order the percent time to peak velocity decreased from IDs3-5 as ID increased and that for the decreasing ID order the percent time to peak velocity decreased from IDs3-6 as ID increased. Simple main effect analysis of the Order × ID also indicated that the percent time to peak velocity was higher for the increasing ID order than the decreasing ID order at ID4 (increasing $M = 43.72\%$, $SE = .883\%$: decreasing $M = 40.84\%$, $SE = .987\%$) and ID6 (increasing $M = 34.64\%$, $SE = .926\%$: decreasing $M = 32.01\%$, $SE = .966\%$) but no difference in percent time to peak velocity between the two orders was detected at ID3 and ID5. No other main effects or interactions were significant.

Harmonicity (H). The analysis of harmonicity detected a main effect of Limb, $F(1, 14) = 24.11$, $p < .01$, and ID, $F(3, 42) = 332.30$, $p < .01$ (see Figure 9G). The H value for the left limb ($M = .48$, $SE = .033$) was slightly higher than right limb ($M = .44$, $SE = .033$). Duncan's multiple range test on ID detected a decrease in H values from ID3 ($M = .92$, $SE = .015$) to ID4 ($M = .65$, $SE = .029$), from ID4 to ID5 ($M = .22$, $SE = .018$), and again from ID5 to ID6 ($M = .05$, $SE = .007$). No other main effects or interactions were significant.

SD of Harmonicity (H). The analysis of standard deviation of harmonicity detected a main effect of ID, $F(3, 42) = 21.95$, $p < .01$. In addition, the Manual x ID interaction, $F(3, 42) = 3.54$, $p < .05$, was significant (see Figure 9H). Simple main effect analysis of the Manual x ID interaction detected that for the bimanual condition the SD of H values increased from ID3 to ID4 and decreased from IDs4-6 as ID increased, however, for the unimanual condition SD of H values increased from ID3 to ID4 and decreased from ID5 to ID6. Simple main effect analysis of the Manual x ID interaction failed to indicate a difference in SD of H values between bimanual and unimanual conditions at ID3 and ID4, but indicated that the SD of H values was smaller for the bimanual than the unimanual condition at ID5 (bimanual $M = .19$, $SE = .017$: unimanual $M = .26$, $SE = .017$) and ID6 (bimanual $M = .05$, $SE = .007$: unimanual $M = .12$, $SE = .013$). No other main effects or interactions were significant.

Bimanual performance

Relative phase. The analysis of relative phase detected a main effect of ID, $F(3, 49) = 6.35$, $p < .01$ (see Figure 10). Duncan's multiple range test on ID detected an decrease in relative phase from IDs3-4 to IDs5-6, but no difference in relative phase was detected between ID3 ($M = 6.13°$, $SE = 1.05°$) and ID4 ($M = 5.05°$, $SE = .54°$) and between ID5 ($M = 3.25°$, $SE = .53°$) and ID6 ($M = 2.25°$, $SE = .49°$). No other main effects or interactions were significant.

SD of relative phase. None of the main effects or interactions was significant.

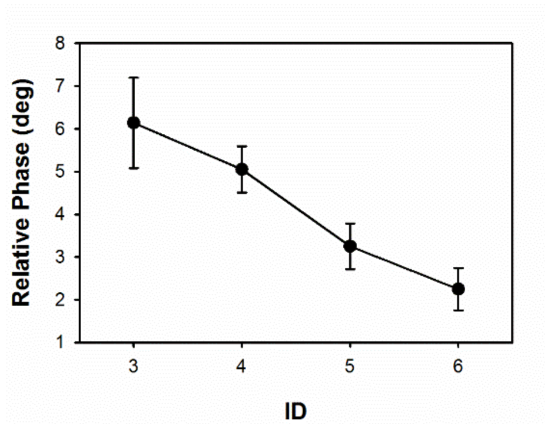

Figure 10. Mean relative phase as a function of ID in Experiment 1. The error bars represent standard error.

Discussion

The bimanual coordination literature has demonstrated that more difficult bimanual coordination patterns (e.g., 1:1 bimanual coordination patterns with a 90° phase offset, multi-frequency coordination patterns) often result in a less stable coupling than the less difficult in-phase or anti-phase coordination patterns. The unimanual aiming literature has demonstrated that increases in task ID result in changes in the unimanual control strategies used to perform the task (Buchanan et al., 2006; Guiard, 1997; Meyer et al., 1988). However, little is known about how changes in this type of constraint affect control strategies in bimanual aiming tasks. The present results indicated that when the accuracy requirements were systematically increased between trials mean relative phase bias was reduced while relative phase variability remained similar across IDs (see Table 1 and Figure 10). The unimanual control processes used in bimanual aiming tasks appear to be similar to the changes in the kinematic features of the movement time series observed in unimanual tasks as the ID is increased or decreased. That is, regardless of whether performances were tested in a decreasing or increasing ID condition, movement time, dwell time, and cycle duration were increased, and percent time to peak velocity was reduced as the ID was increased indicating that more percentage of time was spent on the deceleration phase. In addition, the H value was reduced as the ID was increased. Interestingly, the changes observed in the right (dominate) limb in the unimanual condition were quite similar to the changes observed in the left (non-dominant) limb. Thus, the kinematic data indicates that control strategy changes were similar cross dominant and non-dominant limb as well as when movements were made in the bimanual condition. It should also be noted that the critical ID (ID_c) region noted by Buchanan et al. (2006) also appeared to hold for each limb and in both unimanual and bimanual conditions.

CHAPTER III

EXPERIMENT 2: TARGET WIDTH SCALING WITHIN A TRIAL IN UNIMANUAL AND BIMANUAL AIMING TASKS

Introduction

Experiment 2 also combines bimanual in-phase tasks with Fitts reciprocal aiming tasks to form bimanual reciprocal aiming task. Different from Experiment 1 in which discrete target width scaling occurred between trials, Experiment 2 involved scaling target width within a trial (i.e., ID increased or decreased in 0.5 increments within a trial). Buchanan et al. (2006) have examined participants' right-limb reciprocal aiming performance in a paradigm where the width of the targets within a trial changed while holding the amplitude between the two targets constant. In one condition the target width increased within the trial resulting in decreasing IDs (decreasing ID condition) while in the other condition the target width decreased within the trial resulting in increasing IDs (increasing ID condition). The authors observed that right-limb performance transitioned from cyclical to discrete control when the ID was incrementally increased and transitioned from discrete to cyclical control when the ID was incrementally decreased. In this context cyclical control is consistent with an open-loop description as reflected in shorter movement and dwell times and increased PTPV and H values; discrete control is consistent with a closed-loop description as reflected in longer movement and dwell times and decreased PTPV and H values. Buchanan et al. (2006) noted that transition from cyclical to discrete control and discrete to cyclical control occurred in the region of

IDs 4.0-4.9. This led them to propose a critical ID (ID_c) value of ≈ 4.5 as a boundary to account for the shift between the cyclical and discrete control strategy. In addition, the authors observed an increase in the movement fluctuations (e.g., reflected by increased variability of H values) occurred as they approached the critical ID region. They proposed that this loss of movement stability was associated with the transition of the control strategies.

Experiment 2 extended previous within-trial target width scaling aiming literature using right limb (Buchanan et al., 2006) to left limb performance and to bimanual aiming tasks. The primary purpose of Experiment 2 was to determine the degree to which the change in the difficulty of the movement influences the bimanual control processes and to determine if the control strategies used to perform right-limb aiming tasks are also present in the left-limb and bimanual aiming tasks when target width scaling occurred within a trial. The second purpose was to determine whether the order of presenting ID (i.e., increasing or decreasing ID order) influences the control strategies utilized in bimanual and unimanual aiming tasks when target width scaling occurred within a trial. Note that the smaller scale of ID increment or decrement (0.5) in Experiment 2 allows more precisely determining the critical (ID_c) under increasing and decreasing ID conditions.

In both the unimanual and bimanual conditions, I expect movement at the lower IDs to be controlled in a cyclical manner and movement at the higher IDs to be controlled in a more discrete manner. This will be reflected in the movement kinematics (e.g., deceleration time) and H values. Based on Buchanan et al. (2006) study of the impact of scaling ID on right limb's performance, I predict that as ID increased within a trial, movement time and dwell time will continuously increase and percent time to peak velocity and H values will continuously decrease for both limbs. In addition, based on Buchanan et al. (2006) and Boyle and Shea (2011) study of the impact of ID on upper limb's performance, I also predict that movement time and cycle duration will increase linearly within a trial as a function of ID. Given that the current experimental design requires the participant in the bimanual condition to more tightly couple the two limbs as ID increases, I also predict the relative phase error and relative phase variability will decrease linearly as ID increases within a trial. In addition, based on Buchanan et al. (2006) findings, I predict that the limb's movement will lose stability near the critical ID region. Thus, I predict the largest variability values in SD of RP and SD of H data will be observed near the ID_c value of 4.5, established by Buchanan et al. (2006). I predict that ID_c will occur at a slightly higher ID in the ID increasing order condition and the ID_c value will occur at a slightly lower ID in the ID decreasing order condition as reflected by the harmonicity variability results.

Methods

Participants

Sixteen (6 males, 10 females) Texas A&M college student participants were recruited for Experiment 2. Participant had no prior experience with the experimental task. Participants signed a consent form before entering the testing room. A modified Coren handedness evaluation (Coren, 1993) was used to access participants' handedness.

One participant was classified as left-arm dominant and all the other participants were right-arm dominant.

Apparatus

The apparatus used in Experiment 2 was identical to that used in Experiment 1.

Procedure

Participants were seated in a height adjustable chair in front of the table on which the levers were mounted. In each condition, two target boxes were projected on the wall directly in front of them (see Figure 7). Participants were asked to move the cursor as quickly and accurately as possible between the two targets. Participants were told that they should reverse within the target area. The amplitude between the targets was set at 40°. The width of the target in the direction of movement was manipulated within a trial to create IDs of 2.5 to 6.0 in 0.5 increments or to create IDs of 6.0 to 2.5 in 0.5 decrements. The targets representing each ID will appeared for 7.5 seconds before the target size was changed to accommodate the next ID. Thus, each trial lasts for 60 seconds.

The position of the targets creates bimanual and unimanual conditions for each ID. In the bimanual condition the participants were required to use both arms to perform the task while in the unimanual condition the movement of only one arm would be required. Note that in the Lissajous display left limb movement would move the cursor up (extension) and down (flexion) while movement of the right limb would move the cursor left (flexion) and right (extension). In the bimanual conditions the position of the two targets required participants to produce an in-phase movement (flexing and extending both arms with the same angles) (see Figure 7A, D). In the unimanual conditions, participants only need to move one arm to move between the targets (see Figure 7B, C, E, F).

Each participant was assigned to either a bimanual or unimanual conditions. Each bimanual/unimanual condition included two orders (increasing or decreasing ID). In the increasing bimanual order, participants performed 4 trials in the increasing ID order and 4 trials in the decreasing ID order. The two orders were counterbalanced. In the unimanual left-limb condition, participants used their left limb to control the cursor; in the unimanual right-limb condition participants used their right limb to control the cursor. Similar to the bimanual condition, both unimanual cases involved 4 trials presenting the targets in the increasing ID order and 4 trials presenting the targets in the decreasing ID order. The two orders (i.e., increasing ID and decreasing ID) and the order of the two limbs were counterbalanced.

Data analysis

Trials 4 and 8 (the last trials in the increasing or decreasing order) in the bimanual and unimanual conditions were subjected to data analysis. Data analyses were performed using Matlab (Mathworks, Natick, MA). The determination of displacement, velocity and acceleration is identical to that for Experiment 1. Prior to further data analysis, the displacement time series for each trial were segmented into eight time series (7.5 seconds each) based on the eight ID conditions. The analyses presented focused on bimanual coordination performance of the required in-phase patterns and unimanual performance of the left and right limbs.

Unimanual measurements. The calculation of CD, CDV, MT, DT, PTPV, H values, and SD of H for each ID segment within a trial was identical to that for Experiment 1.

Bimanual measurements. The bimanual measurements for each ID segment were identical to the bimanual measures in Experiment 1.

The RP and SD of RP were analyzed in a separate ID (2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6) × Order (increasing, decreasing IDs) analysis of variance (ANOVA) with repeated measure on both factors. The CD, CDV, MT, DT, PTPV, H values, and SD of H data were analyzed in a Manual (bimanual, unimanual) × ID (2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6) × Order (increasing, decreasing IDs) × Limb (left, right) analysis of variance (ANOVA) with repeated measures on all factors. Significant main effects were further analyzed with Duncan's new multiple range test and significant interactions were further analyzed with simple main effects. An alpha level of .05 will be used for all tests.

Results

Lissajous plot, relative phase, and displacement time series for the last trial (Trials 4 and 8) in the ID increasing and decreasing order for a participant in the bimanual condition are provided in Figure 11. Lissajous plot and displacement time series for the last trial in the ID increasing and decreasing order for a participant in the unimanual condition are provided in Figure 12. The descriptive statistics for bimanual and unimanual measures at different IDs and ID presenting orders are provided in Table 2.

Table 2 Bimanual and unimanual descriptive statistics in Experiment 2.

	Bimanual condition								Unimanual condition							
	ID2.5	ID3	ID3.5	ID4	ID4.5	ID5	ID5.5	ID6	ID2.5	ID3	ID3.5	ID4	ID4.5	ID5	ID5.5	ID6
	M	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*	*M*
CD (*s*) Inc *	0.672	0.691	0.744	0.869	1.082	1.187	1.283	1.411	0.413	0.432	0.483	0.585	0.680	0.766	0.872	1.065
CD (*s*) Dec *	0.605	0.701	0.839	0.944	1.043	1.213	1.406	1.828	0.390	0.451	0.551	0.647	0.770	0.884	0.991	1.190
CDV (*s*) Inc	0.055	0.061	0.077	0.129	0.231	0.255	0.237	0.243	0.044	0.048	0.066	0.089	0.117	0.132	0.172	0.228
CDV (*s*) Dec	0.059	0.063	0.080	0.111	0.123	0.208	0.241	0.453	0.030	0.037	0.059	0.072	0.114	0.142	0.175	0.191
MT (*s*) Inc	0.653	0.675	0.719	0.816	0.947	1.005	1.015	1.100	0.405	0.421	0.471	0.557	0.629	0.690	0.752	0.873
MT (*s*) Dec	0.594	0.689	0.813	0.896	0.965	1.077	1.189	1.323	0.387	0.445	0.538	0.621	0.718	0.799	0.871	1.022
DT (*s*) Inc	0.018	0.016	0.024	0.053	0.088	0.129	0.250	0.311	0.008	0.011	0.012	0.028	0.047	0.070	0.115	0.192
DT (*s*) Dec	0.011	0.012	0.026	0.048	0.078	0.110	0.195	0.463	0.003	0.007	0.012	0.025	0.049	0.082	0.120	0.169
PTPV (%) Inc	41.19	39.39	37.65	34.76	31.60	31.53	30.89	30.93	48.27	47.31	45.03	42.46	40.17	39.89	37.61	33.46
PTPV (%) Dec	43.58	40.48	36.16	34.21	33.59	32.50	30.86	27.29	50.43	47.58	43.63	40.59	37.52	36.38	36.12	31.51
H Inc	0.61	0.49	0.36	0.19	0.07	0.05	0.03	0.01	0.89	0.84	0.76	0.59	0.38	0.28	0.19	0.08
H Dec	0.74	0.57	0.34	0.19	0.15	0.08	0.03	0.01	0.96	0.90	0.72	0.52	0.28	0.18	0.14	0.04
SD of H Inc	0.27	0.29	0.25	0.21	0.09	0.09	0.04	0.02	0.13	0.17	0.23	0.34	0.31	0.22	0.21	0.12
SD of H Dec	0.22	0.28	0.23	0.17	0.08	0.07	0.04	0.02	0.04	0.13	0.25	0.32	0.29	0.21	0.19	0.07
RP (*deg*) Inc	6.12	5.90	3.42	3.06	2.49	2.40	0.65	1.78								
RP (*deg*) Dec	8.57	5.98	4.48	3.31	2.78	2.60	0.39	1.14								
SD of RP (*deg*) Inc	10.07	11.14	9.21	9.46	11.10	11.43	8.51	9.31								
SD of RP (*deg*) Dec	8.63	9.03	9.59	10.55	9.63	11.17	8.53	9.86								

Note. M-mean, Inc-increasing ID order, Dec-decreasing ID order, CD-cycle duration, CDV-cycle duration variability, MT-movement time, DT-dwell time, PTPV-percent time to peak velocity, H-harmonicity, SD of H-standard deviation of harmonicity, RP-relative phase, SD of RP-standard deviation of relative phase. * In this dissertation, the concept of CD and the concept of Total Time (TT), which was calculated by the equation TT = DT + MT, were interchangeable.

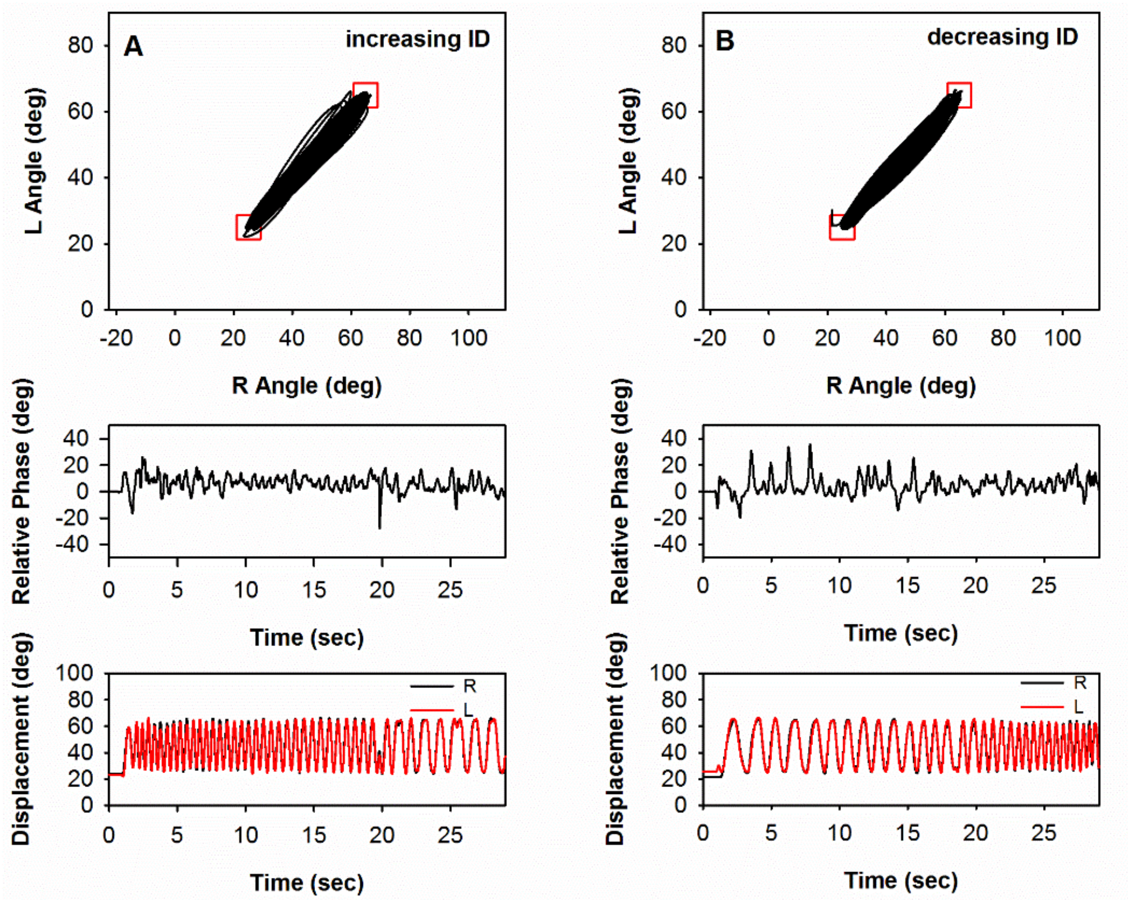

Figure 11. Lissajous plot, relative phase, and displacement time series of the increasing ID (A) and decreasing ID (B) orders for a participant in the bimanual condition. Note that the target size changed from large to small and from small to large within a trial in the increasing ID and decreasing ID conditions, respectively.

Unimanual performance

Cycle duration. The analysis of cycle duration detected a main effect of Manual, $F(1, 14) = 31.56$, $p < .01$, and ID, $F(7, 98) = 213.99$, $p < .01$. In addition, the Manual × ID interaction, $F(7, 98) = 4.69$, $p < .01$, the Order × ID interaction, $F(7, 98) = 9.23$, $p < .01$, and the Manual × Order × ID interaction, $F(7, 98) = 4.25$, $p < .01$ (see Figure 13A), were significant. Simple main effect analysis of the Order × ID interaction for both manual conditions indicated that the cycle duration for the increasing ID order increased as ID increased for 1 unit started from ID3 and the cycle duration for the decreasing ID order increased as ID increased for 1 unit started from ID2.5. Simple main effect

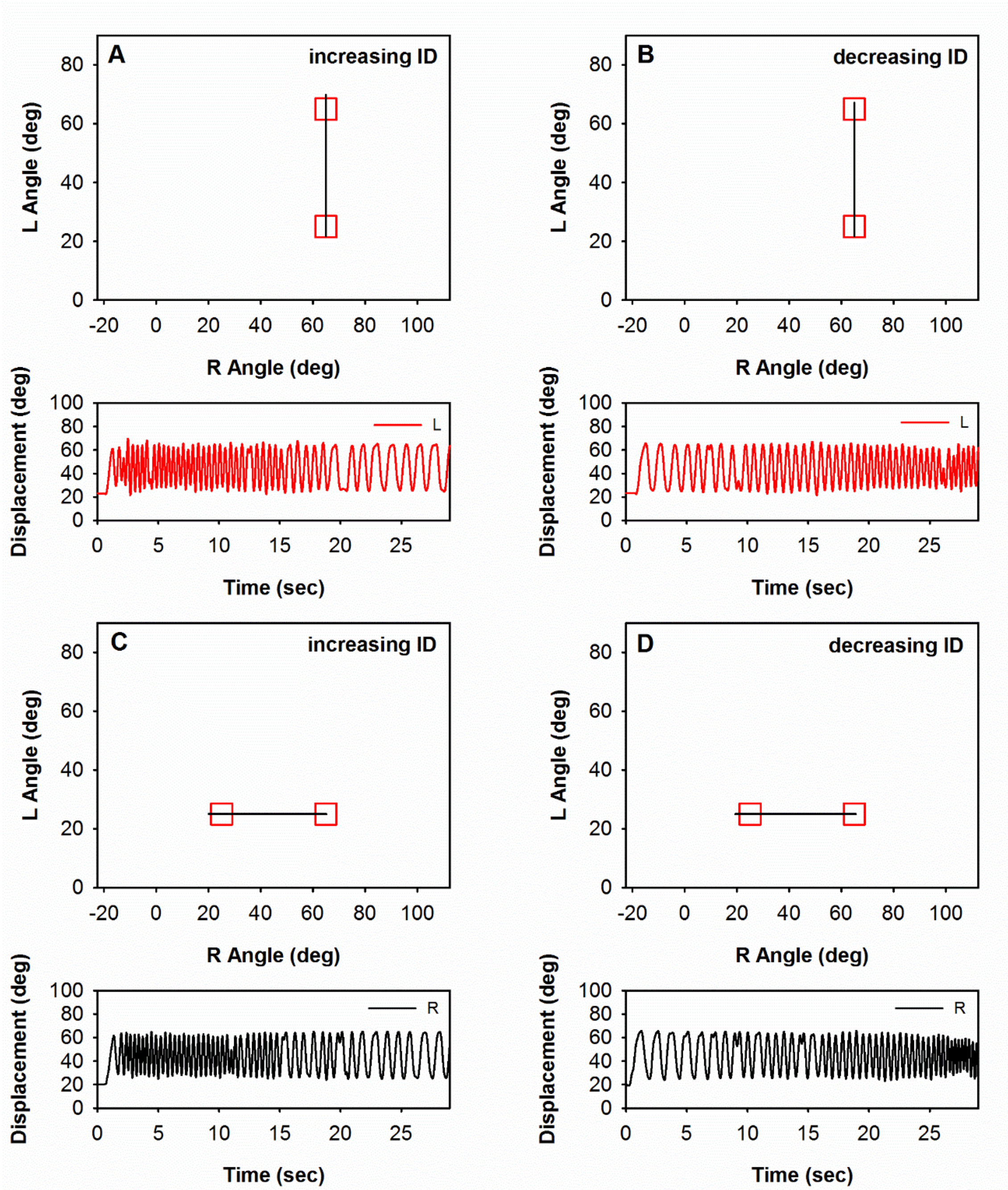

Figure 12. Lissajous plot and displacements of increasing ID order (A,C) and decreasing ID order (B,D) of the left (A,B) and right (C, D) limb for a participant in the unimanual condition.

analysis of the Order × ID interaction for the bimanual condition failed to detect a difference in cycle duration between the two orders at IDs2.5-5 but detected the cycle duration for the decreasing ID order was longer than for the increasing ID order at IDs5.5-6. Simple main effect analysis of the Order × ID interaction for the unimanual condition failed to detect a difference in cycle duration between the two orders at IDs2.5-4 but detected the cycle duration for the decreasing ID order was longer than for the increasing ID order at IDs4.5-6.

Cycle duration variability. The analysis of cycle duration variability detected a main effect of Manual, $F(1, 14) = 14.14$, $p < .01$, and ID, $F(7, 98) = 53.61$, $p < .01$. In addition, the Manual × ID interaction, $F(7, 98) = 3.59$, $p < .05$, the Order × ID interaction, $F(7, 98) = 3.52$, $p < .01$, and the Manual × Order × ID interaction, $F(7, 98) = 5.82$, $p < .01$ (see Figure 13B), were significant. Simple main effect analysis of the Order × ID interaction for the bimanual condition indicated that the cycle duration variability for the increasing ID order increased as ID increased for 1 unit from IDs3-5 but the difference between IDs was not significant for IDs2.5-3 and for IDs4.5-6, however, the cycle duration variability for the decreasing ID order increased as ID increased for 1 unit from IDs5-6 but no difference was detected between IDs for IDs2.5-4.5. Simple main effect analysis of the Order × ID interaction for the unimanual condition indicated that the cycle duration variability for both orders increased as ID increased for 1 unit from IDs3-6 but the difference between IDs was not significant for IDs2.5-3.5. Simple main effect analysis of the Order × ID interaction for the bimanual condition also detected that the cycle duration variability for the increasing ID order was larger than for the decreasing ID order at ID4.5 and the cycle duration variability for the increasing ID order was smaller than for the decreasing ID order at ID6, but no difference in cycle duration variability was detected between the two orders at other IDs. Simple main effect analysis of the Order × ID interaction for the unimanual condition also detected that the cycle duration variability for the increasing ID order was larger than for the decreasing ID order at ID6, but no difference in cycle duration variability was detected between the two orders at other IDs.

Movement time. The analysis of movement time detected a main effect of Manual, $F(1, 14) = 32.34$, $p < .01$, ID, $F(7, 98) = 163.85$, $p < .01$, and Order, $F(1, 14) = 4.94$, $p < .05$. In addition, the Order × ID interaction, $F(7, 98) = 9.91$, $p < .01$, was significant (see Figure 13C). The movement time for the bimanual condition ($M = .904$s, $SE = .016$s) was longer than the unimanual condition ($M = .637$s, $SE = .013$s). Simple main effect analysis of the Order × ID interaction indicated that the movement time for both orders increased as ID increased for 1 unit. Simple main effect analysis of the Order × ID interaction also indicated that the movement time was faster for the increasing ID order than the decreasing ID order at IDs5-6, but the difference in movement time between the two orders was not significant at the other IDs. No other main effects or interactions were significant.

Dwell time. The analysis of dwell time detected a main effect of Manual, $F(1, 14) = 10.23$, $p < .01$, and ID, $F(7, 98) = 41.13$, $p < .01$. In addition, the Manual × ID interaction, $F(7, 98) = 5.30$, $p < .01$, was significant (see Figure 13D). Simple main effect analysis of the Manual × ID interaction indicated that the dwell time for the bimanual condition increased as ID increased for 1 unit from IDs4-6 but the difference in dwell time between IDs was not significant for IDs2.5-4.5, however, the dwell time for the unimanual condition increased as ID increased for 1 unit from IDs4.5-6 but the difference in dwell time between IDs was not significant for IDs2.5-5. Simple main effect analysis of the Manual × ID interaction also indicated that dwell time was longer for the bimanual than the unimanual condition at IDs5.5-6 but the difference in dwell time between the two manual conditions was not significant at IDs2.5-5. No other main effects or interactions were significant.

Percent time to peak velocity. The analysis of percent time to peak velocity detected a main effect of Manual, $F(1, 14) = 26.28$, $p < .01$, and ID, $F(7, 98) = 71.92$, $p < .01$. In addition, the Order × ID interaction, $F(7, 98) = 3.77$, $p < .01$, was significant (see Figure 14E). The percent time to peak velocity for the unimanual condition (M = 41.121%, SE = .433%) was higher than the bimanual condition (M = 34.788%, SE = .399%). Simple main effect analysis of the Order × ID interaction indicated that the percent time to peak velocity decreased as ID increased for both the ID increasing and decreasing orders. Simple main effect analysis of the Order × ID interaction also indicated that the percent time to peak velocity was larger for the decreasing ID order than the increasing ID order at ID2.5 but was larger for the increasing ID order than the decreasing ID order at ID6, however, the difference in percent time to peak velocity between the two orders was not detected at IDs3-5.5. No other main effects or interactions were significant.

Harmonicity (H). The analysis of harmonicity detected a main effect of Manual, $F(1, 14) = 19.45$, $p < .01$, Limb, $F(1, 14) = 8.64$, $p < .05$, and ID, $F(7, 98) = 113.79$, $p < .01$. In addition, the Manual × ID interaction, $F(7, 98) = 4.85$, $p < .01$ (see Figure 13F) was significant. The H values for the left limb ($M = .392$, $SE = .022$) was higher than for the right limb ($M = .337$, $SE = .022$). Simple main effect analysis of the Manual × ID interaction indicated that the H values for the bimanual condition decreased as ID increased for 1 unit from IDs2.5-5 but the difference between IDs was not significant for IDs4.5-6, however, the H values for the unimanual condition decreased as ID increased for 1 unit for all IDs. Simple main effect analysis of the Manual × ID interaction also indicated that the H value was lower for the bimanual than the unimanual condition at IDs2.5-5, but the difference between the two manual conditions was not significant at IDs5.5-6.

SD of Harmonicity (H). The analysis of standard deviation of harmonicity detected a main effect of Manual, $F(1, 14) = 25.38$, $p < .01$, Limb, $F(1, 14) = 7.51$, $p < .05$, and ID, $F(7, 98) = 13.78$, $p < .01$. In addition, the Manual × Limb interaction, $F(1, 14) = 5.84$, $p < .05$ (see Figure 13G), and the Manual × ID interaction, $F(7, 98) = 15.28$, $p < .01$ (see Figure 13H), were significant. Simple main effect analysis of the Manual × Limb interaction indicated that the SD of H values of the left limb was larger than the right limb for the bimanual condition, but the difference in SD of H values between the two limbs was not significant for the unimanual condition. Simple main effect analysis of the Manual × Limb interaction also indicated that the SD of H value was larger for the unimanual than the bimanual condition for the right limb, but the difference in SD of H

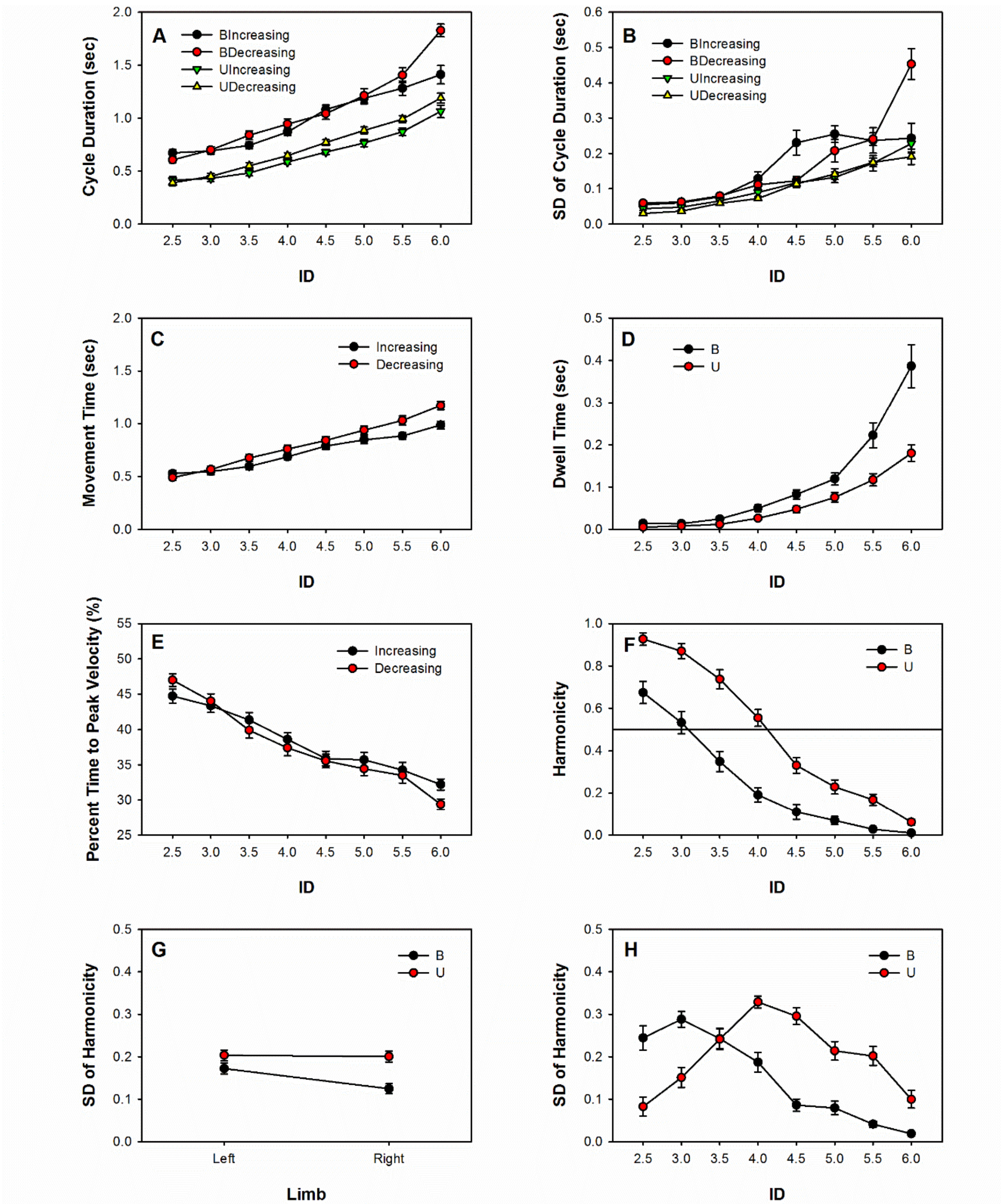

Figure 13. Mean cycle duration (A), cycle duration variability (B), movement time (C), dwell time (D), percent time to peak velocity (E), harmonicity (F), and harmonicity variability (H) for the bimanual ("B") and unimanual ("U") condition and/or the increasing or decreasing ID order as a function of ID. Mean harmonicity variability for the left and right limb condition for the bimanual and unimanual condition (G). The error bars represent standard error.

values between the two manual conditions was not significant for the left limb. Simple main effect analysis of the Manual × ID interaction indicated that the SD of H values for the bimanual condition decreased as ID increased for 1 unit from IDs3-5 but the difference between the IDs was not significant for IDs2.5-3.5 and for 4.5-6, however, the SD of the H values for the unimanual condition increased as ID increased for 1 unit from IDs2.5-4 but decreased as ID increased for 1 unit from IDs4-6. Simple main effect analysis of the Manual × ID interaction also indicated that the SD of H values was larger for the bimanual than the unimanual condition at ID2.5 and ID3, the difference in SD of H values between the two manual conditions was not significant at ID3.5, and the SD of H value was smaller for the bimanual than the unimanual condition at IDs4-6. No other main effects or interactions were significant.

Bimanual performance

Relative phase. The analysis of relative phase detected a main effect of ID, $F(7, 105) = 8.12$, $p < .01$ (see Figure 14). Duncan's multiple range test on ID indicated that relative phase values for IDs2.5-3 were significant higher than the other IDs, however, the difference in relative phase between adjacent IDs was not significant for IDs2.5-3 and for IDs3.5-5.

SD of relative phase. None of the main effects or interactions was significant.

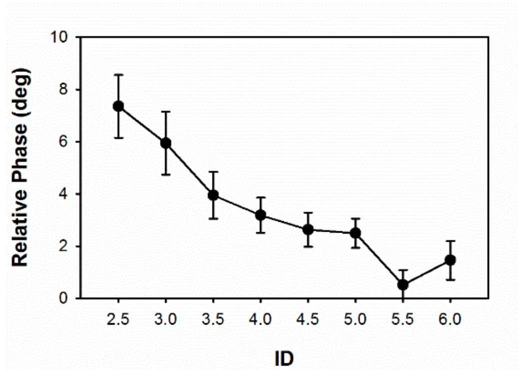

Figure 14. Mean relative phase as a function of ID in Experiment 2. The error bars represent standard error.

Discussion

In Experiment 2, ID was systematically increased within a trial. The data indicated that in both unimanual and bimanual conditions the end-effectors' motion gradually switched from a cyclical motion to a discrete motion as ID increased and switched from discrete to cyclical motion as the ID was systematically decreased. This switch in control strategies is indicated by increased movement time, DT, and cycle duration, and by reduced PTPV and H values regardless of the manual or limb used or the increasing or decreasing order of presenting IDs (see Table 2). The directions of change in dependent limb measurements as influenced by ID in Experiment 2 are consistent with Experiment 1 and other unimanual aiming studies (Buchanan et al., 2006; Guiard, 1993, 1997). In terms of bimanual coordination, mean relative phase bias decreased as ID increased within a trial but maintained the same variability (see Table 2).

CHAPTER IV

EXPERIMENT 3: ARE BIMANUAL CONTROL STRATEGIES INFLUENCED BY THE ELEMENT DIFFICULTY?

Introduction

As noted in Chapter I, the bimanual coordination literature has consistently argued that bimanual control is in many situations relatively more difficult than unimanual control especially when the task requires the two limbs to produce different movement patterns. Kelso, Southard & Goodman (1979a, b), for example, demonstrated that bimanual aiming movements to targets of different widths and amplitudes were produced more slowly than when the tasks were produced unimanually, although this difference was minimal when the amplitude and target width for the two limbs in the bimanual conditions were the same and the response required the simultaneous activation of homologous muscles. The bimanual literature has also repeated demonstrated that a 1:1 in-phase coordination pattern is highly stable while other phase offsets are less stable and some multi-frequency coordination patterns are significantly more difficulty to perform. This was clearly demonstrated in experiments using scanning trials (e.g., Yamanishi et al., 1980; Zanone & Kelso, 1992) where coordination errors and variability for all phase offsets tested were significantly higher than for the in-phase (0° phase offset), although the anti-phase (180°) coordination pattern was also produced in a relatively stable manner. These findings led researcher to conclude that relative phase patterns other than in-phase and anti-phase are inherently unstable and the motor system shows a bias toward what has been labeled as the intrinsic dynamics of in-phase and anti-phase coordination (Schoner & Kelso, 1988).

The bimanual coordination research has also shown that in-phase coordination patterns are more stable than anti-phase coordination patterns (Kelso, 1981; Kelso, 1984; Kelso et al., 1986) and that when cycle frequency is increased participants sometimes spontaneously transition from anti-phase to in-phase but not from in-phase to anti-phase (see Beek, Peper, & Stegeman, 1995, for review). In addition, research on the production of bimanual multi-frequency ratios (e.g., 1:2, 2:3, 3:5 ratios), which are considered significantly more difficult to perform (see Peper et al., 1995, for discussion; Shea, Buchanan, & Kennedy, 2015, for review), often shows signs that participants spontaneously transition to more stable 1:1 or lower order frequency relationships while performing these polyrhythmic coordination patterns (e.g., Treffner & Turvey, 1993). Buchanan and Ryu (2006) provided evidence that participants sometimes spontaneously produce multi-frequency patterns for brief time periods when 1:1 pattern becomes unstable (also see Buchanan & Ryu, 2012).Thus, when attempting to produce phase or frequency relationships other than 1:1 in-phase, the instability of the coordination pattern could result in the movement of one limb toward the pattern of movement of the other limb resulting in a phase transition to a more stable (e.g., 1:1 in-phase) coordination pattern (see Beek et al., 1995, for a review). We interpret these results to mean that participants when faced with a novel movement task will choose to utilize unimanual control strategies over bimanual control strategies when permitted by the task constraints. We also interpret these finding to suggest that when more than one bimanual control strategy could be used to perform a task participants will choose to complete the task using a more stable coordination pattern over a less stable coordination pattern especially when one of the goals is to move as quickly and smoothly as possible.

In addition, the unimanual aiming literature has repeatedly demonstrated that increases in task difficulty (ID) result in changes in control strategies used to perform the task (e.g., Buchanan et al., 2006; also see Experiments 1 and 2). However, little is known about how changes in this type of constraint affect the changes in control strategies in bimanual aiming tasks. Presumably, increases in ID will result in shifts to more stable control strategies and greater online processing of the movement.

The tasks used in Experiment 3 were designed so that they could be completed using more than one bimanual coordination strategy. Task A was designed so that the participant could complete the task using either unimanual or bimanual control strategies (see Figure 15A,B). Task B (see Figure 15G,H) was designed so that participants could complete the task using relatively simple (in-phase and anti-phase) or more difficult bimanual control strategies (1:1 with 90º phase offset). Although the bimanual coordination literature suggests that participants will tend to choose more stable coordination patterns over less stable patterns (Fontaine et al., 1997; Haken et al., 1985; Schoner et al., 1986; Schoner & Kelso, 1988; Zanone & Kelso, 1992), there is little literature that has directly compared participants' preference when facing a choice of performing different unimanual/bimanual control strategies. Participants may choose more stable unimanual/bimanual coordination strategies (e.g., unimanual control) or a less stable bimanual coordination strategies (e.g., 1:1 bimanual with 90° relative phase) to move a cursor between targets in the Lissajous display. For example, if the performer perceives the four target arranged in a square (Task A) or diamond (Task B) shape as a single task, a circular movement path in the Lissajous feedback display may result with the participant using a bimanual 1:1 with 90° relative phase coordination strategy (Fontaine et al., 1997; Attila J Kovacs, Buchanan, & Shea, 2009b; Zanone & Kelso, 1992). Alternatively, if the performer perceives the task as a series of independent movements, they may attempt hit the targets in a linear fashion one by one. If this is the case, straight paths will result from alternating left and right limb unimanual control in Task A or bimanual 1:1 (in-phase and anti-phase) coordination pattern in Task B.

Note that Lissajous displays were used in the present experiment. This type of display has been shown to decrease perceptual and attentional constraints that influence the production of many bimanual coordination patterns. In fact, many bimanual control patterns that have been thought to be difficult, if not impossible, to produce without extended practice have been effectively produced following only minutes of practice when Lissajous or other integrated displays were used (e.g., Kovacs et al., 2010a, 2010b; Preilowski, 1972). Thus, participants may be more likely to choose what are commonly thought to be more difficult control strategies because some of the perceptual and attentional constraints normally impinging on the performance of these tasks are minimized by the Lissajous display.

The purpose of the study is to determine the unimanual and bimanual coordination strategies participants utilize to complete two movement tasks and determine the degree to which the size of the targets influences the coordination strategy chosen. Each task will consist of 4 targets that the participants cycle through in a specific order. Participants will be asked to move through (hit) as many of the targets as possible in each 30 sec trial and will be encouraged to increase the hit rate over practice. Presumably, participants will choose more stable unimanual/bimanual coordination strategies over more difficult/less stable bimanual coordination strategies to complete the various tasks especially when the ID is increased (target size decreased). Given previous literature, we would predict that participants will consistently choose more stable coordination patterns over less stable coordination patterns (Haken et al., 1985; Schoner et al., 1986; Yamanishi et al., 1980) particularly when accuracy requirements are increased. However, given the recent findings that Lissajous displays greatly reduce perceptual and attentional constraints on bimanual control, it would not be unexpected for more difficult patterns of bimanual coordination (e.g., bimanual 90° relative phase) to emerge as participants attempt to efficiently move through the target sequence.

Methods

Participants

Sixteen (9 males, 7 females) Texas A&M college student participants were recruited for Experiment 3. Participants had no prior experience with the experimental task and were not informed of the control options. Participants signed a consent form approved by the Texas A&M University IRB before entering the test room. A modified Coren handedness evaluation (Coren, 1993) was used to access participants' handedness. All participants were classified as right-arm dominate.

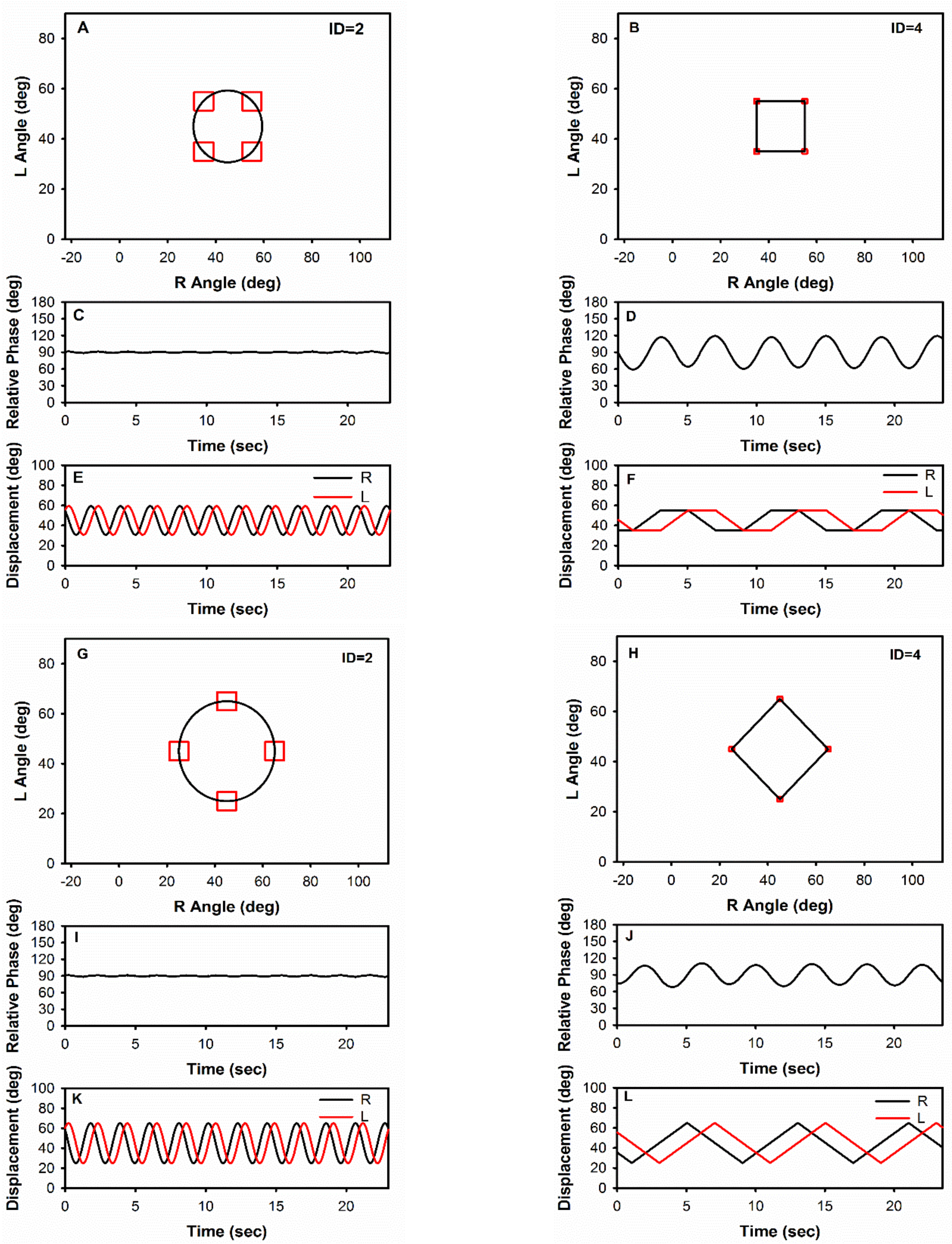

Figure 15. Lissajous plots, relative phase, displacement for simulated left and right limb movements that result in a perfect 1:1 with 90° relative phase in Task A, ID2 condition (A,C,E) and Task B, ID2 condition (G,I,K). Simulated left and right limb sequence of direct movements in the Task A, ID4 condition (B,D,F) and Task B, ID4 condition (H,J,L).

Apparatus

The apparatus used in Experiment 3 was identical to that used in Experiments 1 and 2 with the exception of the program used to display the targets and process the on-line path.

Procedure

Prior to entering the testing room participants were assigned to one of the two tasks (A or B). Each task included two conditions: ID2 and ID4. Task A and B differed in terms of the position of the targets. Participants were seated in a height adjustable chair in front of the table on which the levers were mounted. Prior to introducing the tasks, participants were provide a 30 sec period to move the cursor on the screen. The position of the cursor was controlled in a similar way as in Experiment 1 and 2. That is, left limb movement would move the cursor up (extension) and down (flexion) while movement of the right limb would move the cursor left (flexion) and right (extension). To begin a trial, four target boxes were positioned (depending on the task) in the Lissajous display projected on the screen in front of the participant. Participants were told that the trial begins when one of the target boxes was illuminated and the task was to move the cursor to the illuminated target as fast and accurately as possible. Upon achieving the target (when both limbs were in the target area), the illumination was turned off and the next box in the sequence was immediately illuminated. Participants were told that the goal was to move cursor to the target area and hit as many illuminated target boxes as possible in each trial. Participants were not provided any information on potential control strategies. At the end of a trial, the number of hits was displayed on the screen and the participant was encouraged to increase this number from trial to trial. In each of the tasks, the horizontal/vertical distance/amplitude between two adjacent center of the targets (A = 20°) and the width of the target (W = 10° or 2.5°) resulted in an ID of 2 in one condition and an ID of 4 ($ID = \log_2(2A/W)$, Fitts, 1954) in the other condition. The order in which the participants practiced the ID2 and ID4 conditions was counterbalanced. The targets in Task A were arranged in a square shape (Figure 15A, B) and the targets were illuminated in a counter-clockwise order. This task could be produced using a series of unimanual left and right limb movements or could be performed using a more difficult 1:1 with 90° phase offset bimanual coordination strategy. The targets in Task B were arranged in the diamond shape (Figure 15G, H) and were illuminated in a counter-clockwise order. This task could be performed by connecting the targets in a series of linear paths on the Lissajous plot or by connecting the targets through a circular path on the Lissajous plot resulting in a continuous 1:1 bimanual coordination pattern with 90° phase offset. For both tasks, each participant practiced 15 trials for both ID2 and ID4 conditions (order counter-balanced). Following the completion of practice, a test trial was administered under each ID condition (order counterbalanced). Each trial was 30 seconds.

Data analysis

All data analyses will be performed using Matlab (Mathworks, Natick, MA). The determination of displacement, velocity and acceleration are identical to that for Experiment 1. The analyses presented will focus on task performance (segment movement time, and hits) across acquisition and test trials. Other unimanual and bimanual measures will be analyzed on the test trials for each task and ID condition.

Task performance. The time required to move from one target to the next was termed segment movement time and the number of targets hit during the trial was termed hits. Segment movement time was determined as the time from when both limbs exited one target area to the time they entered next target area. Note that this time excludes time in the target area. Segment movement time variability was defined as the standard deviation of the segment movement times across the trial. Hit number were defined as the number of targets achieved during the course of the 30 s trial.

Unimanual measurements. The calculation of MT, DT, PTPV, H values, and SD of H for each limb was identical to that for Experiment 1.

Bimanual measurements. The bimanual measurements within a trial were identical to the bimanual measures in Experiment 1. In addition, tangential velocity (TV) was calculated based on both lever velocities. Tangential velocity (TV) and tangential velocity variability were defined as the mean and standard deviation (SD) of the tangential velocity time series across trial. Tangential velocity time series in Experiment 3 provide information on the degree to which the coordination pattern resulted in continuous or discrete bimanual movement of the cursor.

Segment movement time, segment movement time variability, hit number, mean RP, SD of RP, mean TV, and SD of TV for each task and condition will be analyzed in a Task (A, B) × ID (2, 4) ANOVA with repeated measures on ID. MT, DT, PTPV, and H values data will be analyzed in a separate Task (A, B) × ID (2, 4) × Limb (left, right) analysis of variance (ANOVA) with repeated measures on Limb and ID. Significant main effects will be further analyzed with Duncan's new multiple range test and significant interactions will be further analyzed with simple main effects. An alpha level of .05 will be used for all tests.

Results

Displacement, velocity, Lissajous plot, phase portrait (velocity vs. position), tangential velocity, and relative phase at ID2 and ID4 for a participant on each task are provided in Figure 16. Mean segment movement time and hit number for every three practice trials and the test trial for each task and ID condition are provided in Figure 17 (A, B). Bimanual measures of relative phase, relative phase variability, tangential velocity and tangential velocity variability are also included in Figure 17 (C-F). Descriptive statistics for bimanual and unimanual measures at different IDs and limbs are provided in Table 3. Unimanual measures of movement time, dwell time, percent time to peak velocity, harmonicity, and harmonicity variability are provided in Figure 18.

Task performance

Segment movement time. The acquisition analysis for segment movement time (see Figure 17A) indicated a main effects of Task, $F(1, 14) = 4.61$, $p < .05$, with movement time longer for Task B ($M = .861$ s, $SE = .070$ s) than for Task A ($M = .670$ s, $SE = .058$ s). The main effects of ID, $F(1, 14) = 55.91$, $p < .01$, and Trial, $F(4, 56) = 35.73$, $p < .01$, were also significant. In addition the ID × Trial interaction was significant, $F(4, 56) = 5.00$, $p < .01$. Simple main effects analysis of the Trial × ID interaction indicated that the segment movement time for ID4 conditions decreased from Trials 1-3 to Trials 4-6, however, no significant difference between trials was detected for ID2 conditions. Simple main effect analysis of the Trial × ID interaction also indicated that the segment movement time was longer for ID4 than ID2 for all trials.

The analysis of segment movement time on the test trial (see Figure 17A) indicated main effects of Task, $F(1, 14) = 6.92$, $p < .05$, with segment movement time longer for Task B ($M = .684$ s, $SE = .101$ s) than for Task A ($M = .514$ s, $SE = .077$ s), and ID, $F(1, 14) = 121.5$, $p < .01$, with segment movement time increasing from the ID = 2 condition ($M = .288$ s, $SE = .013$ s) to the ID = 4 condition ($M = .909$ s, $SE = .046$ s).

Hit number. The acquisition analysis of hit number (see Figure 17B) indicated main effects of ID, $F(1, 14) = 61.64$, $p < .01$, and Trial, $F(4, 56) = 48.57$, $p < .01$. In addition the ID × Trial interaction was significant, $F(5, 56) = 11.02$, $p < .01$. Simple main effects analysis of the Trial × ID interaction indicated that the number of hits for ID2 condition increased over practice from Trials1-3 to Trials 9-12 and the number of hits for ID4 increased from Trials 1-3 to Trials 4-6. Simple main effect analysis of the Trial × ID interaction also indicated that the number of hits was higher for ID2 than ID4 for all trials.

The analysis of hit number (see Figure 17B) on the test trial indicated only a main effect of ID, $F(1, 14) = 93.51$, $p < .01$, with the number of hits decreasing from the ID = 2 condition ($M = 87.25$, $SE = 6.13$) to the ID = 4 condition ($M = 33.43$, $SE = 1.55$).

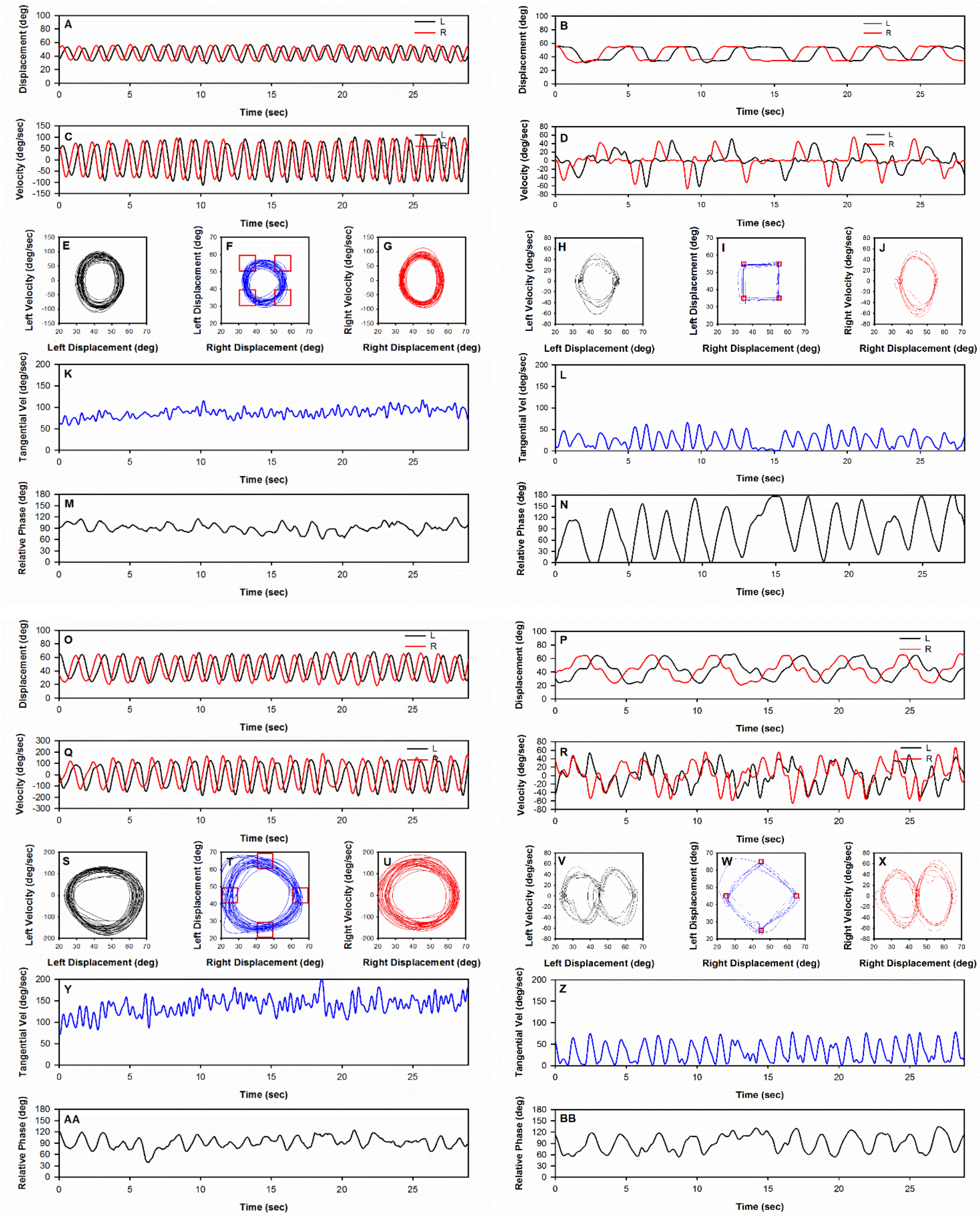

Figure 16. Sample displacement, velocity, Lissajous plot, velocity-displacement phase plot, tangential velocity, and relative phase for Task A, ID2 condition (top, left) and Task B, ID2 condition (bottom, left). Sample plots for Task A, ID4 condition (top, right) and Task B, ID4 condition (bottom, right). Note that the relative phase plot (N) maybe misleading because participants tended to choose unimanual control strategies.

Table 3 Bimanual and unimanual descriptive statistics in Experiment 3.

	Task A (square shape)		Task B (diamond shape)	
	ID = 2	ID = 4	ID = 2	ID = 4
	M	*M*	*M*	*M*
MT (*s*) L	0.606	0.895	0.714	1.237
MT (*s*) R	0.607	0.804	0.711	1.235
DT (*s*) L	0.018	0.858	0.019	0.177
DT (*s*) R	0.018	0.961	0.019	0.232
PTPV (%) L	51.19	46.64	46.90	42.33
PTPV (%) R	51.34	43.97	48.38	41.79
Harmonicity L	0.76	0.03	0.63	0.18
Harmonicity R	0.67	0.05	0.51	0.07
Segment MT (*s*)	0.235	0.792	0.341	1.026
SD of Segment MT (*s*)	0.02	0.05	0.02	0.07
Hit number	97.75	35.25	76.75	31.63
Relative phase (*deg*)	95.70	91.90 *	94.04	92.91
SD of Relative phase (*deg*)	14.69	46.78 *	14.56	18.23
Tangential velocity (*deg/s*)	64.18	25.95	89.33	34.60
SD of Tangential velocity (*deg/s*)	10.83	15.03	15.28	14.91

Note. M-mean, SD-standard deviation, L-left limb, R-right limb, MT-movement time, DT-dwell time, PTPV-percent time to peak velocity. * Note that the relative phase measurement maybe misleading because participants tended to choose unimanual control strategies.

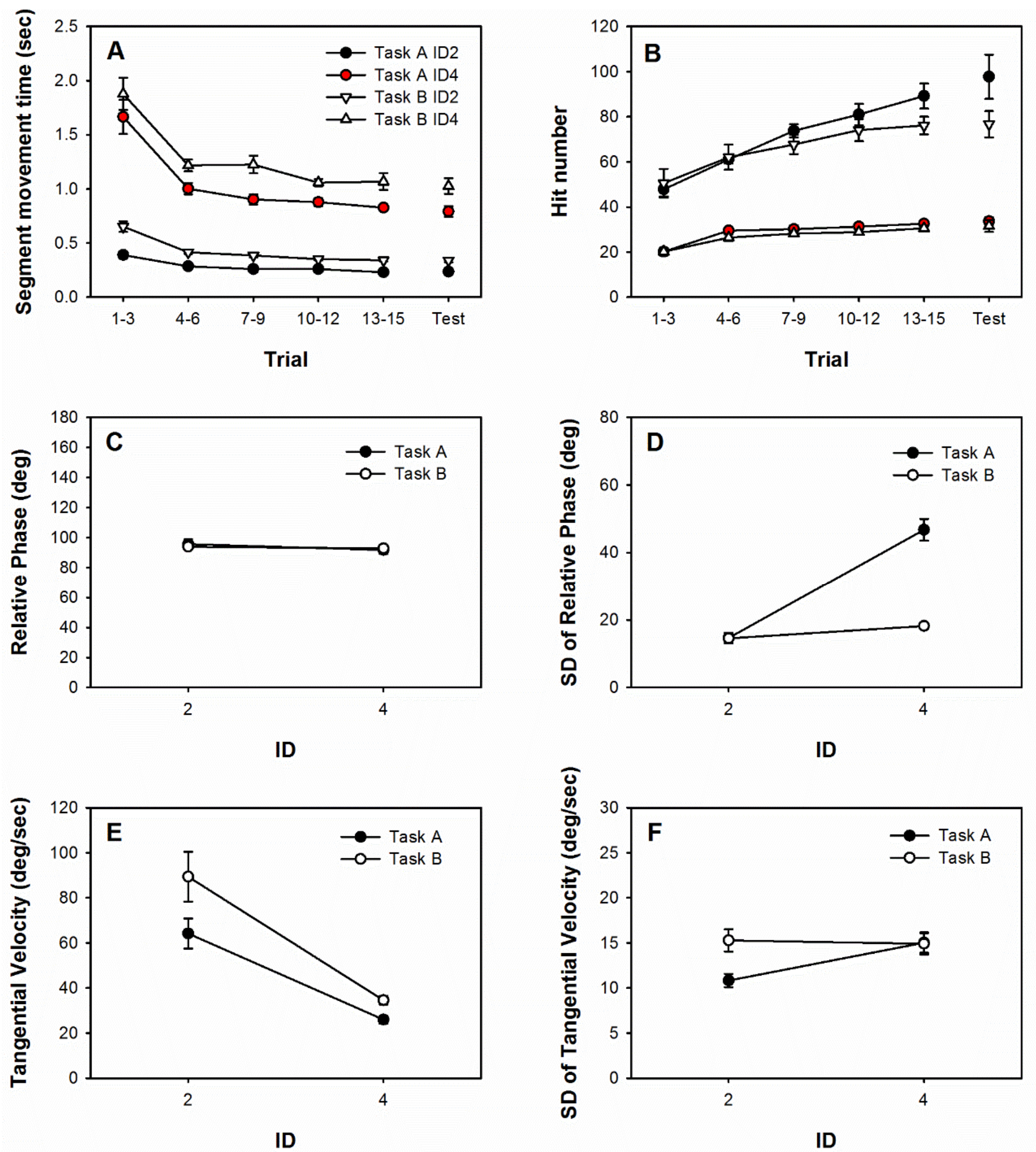

Figure 17. Mean segment movement time (A) and hit number (B) for every three practice trials and the test trial for each task and ID condition. Bimanual measures of mean relative phase (C), relative phase variability (D), tangential velocity (E), and tangential velocity variability (F) for each task and ID on the test trial. Error bars represent standard error.

Bimanual performance

Relative phase. The analysis of mean relative phase failed to detect any main effects or interactions (see Figure 17C). Note, however, that the relative phase values for Task A at ID2 condition may be misleading because participants tended to choose unimanual control strategies.

SD of relative phase. The analysis of relative phase variability detected a main effect of Task, $F(1, 14) = 47.56$, $p < .01$, and ID, $F(1, 14) = 98.63$, $p < .01$. In addition, the Task × ID interaction, $F(1, 14) = 62.30$, $p < .01$, was significant (see Figure 17D). Simple main effect analysis of the Task × ID interaction indicated that relative phase variability for Task A was larger at ID4 ($M = 46.78^{o}$, $SE = 3.23^{o}$) than ID2 ($M = 14.68^{o}$, $SE = 1.53^{o}$), but the difference in relative phase variability between the two IDs for Task B was not significant. Task B. Simple main effect analysis of the Task × ID interaction also indicated that the relative phase variability was larger for Task A ($M = 46.78^{o}$, $SE = 3.23^{o}$) than Task B ($M = 18.23^{o}$, $SE = .89^{o}$) at ID4 but no difference in relative phase variability between the two tasks was detected at ID2.

Tangential velocity. The analysis of tangential velocity detected a main effect of Task, $F(1, 14) = 5.28$, $p < .05$, and ID, $F(1, 14) = 66.65$, $p < .01$ (see Figure 17E). The average tangential velocity for Task B ($M = 61.96^{o}/s$, $SE = 8.90^{o}/s$) was larger than for Task A ($M = 45.06^{o}/s$, $SE = 5.95^{o}/s$). The tangential velocity for ID2 ($M = 76.75^{o}/s$, $SE = 7.02^{o}/s$) was larger than for ID4 ($M = 30.27^{o}/s$, $SE = 1.65^{o}/s$). The Task × ID interaction was not significant.

SD of Tangential velocity. The analysis of tangential velocity variability detected a Task × ID interaction, $F(1, 14) = 5.69$, $p < .05$ (see Figure 17F). Simple main effect analysis of the Task × ID interaction indicated that tangential velocity variability for Task A was larger for ID4 (M = 15.02°/s, SE = 1.12°/s) than for ID2 (M = 10.82°/s, SE = 0.73°/s), but the difference in tangential velocity variability between the two IDs was not significant for Task B. Simple main effect analysis of the Task × ID interaction also indicated that the tangential velocity variability was smaller for Task A (M = 10.82°/s, SE = .73°/s) than for Task B (M = 15.28°/s, SE = 1.23°/s) at ID2, but no difference in tangential velocity variability between the two tasks was detected at ID4. None of the main effects was significant.

Unimanual performance

Movement time. The analysis of movement time detected a main effect of Task, $F(1, 14) = 12.05$, $p < .01$, and ID, $F(1, 14) = 40.88$, $p < .01$. In addition, the Task × ID interaction, $F(1, 14) = 5.48$, $p < .01$, was significant (see Figure 18A). Simple main effect analysis of the Task × ID interaction indicated that the movement time for both tasks was longer at ID4 than ID2 (Task A-ID2 M = .606s, SE = .040s: Task A-ID4 M = .849s, SE = .039s; Task B-ID2 M = .712s, SE = .050s: Task B-ID4 M = 1.236s, SE = .056s). Simple main effect analysis of the Task × ID interaction also indicated that the movement time was longer for Task B than Task A at ID4, but no difference in movement time between the two tasks was detected at ID2. No other main effects or interactions were significant.

Dwell time. The analysis detected a main effect of Task, $F(1, 14) = 47.17$, $p < .01$, Limb, $F(1, 14) = 6.99$, $p < .05$, and ID, $F(1, 14) = 111.75$, $p < .01$. In addition, the Task × ID interaction, $F(1, 14) = 47.94$, $p < .01$ (see Figure 18B), and the Limb × ID interaction, $F(1, 14) = 7.35$, $p < .01$ (see Figure 18C), were significant. Simple main effect analysis of the Task × ID interaction indicated that the dwell time for both tasks was longer at ID4 than ID2 (Task A-ID2 *M* = .017s, *SE* = .002s: Task A-ID4 *M* = .909s, *SE* = .067s; Task B-ID2 *M* = .018s, *SE* = .003s: Task B-ID4 *M* = .204s, *SE* = .031s). Simple main effect analysis of the Task × ID interaction also indicated that the dwell time was longer for Task A than Task B at ID4, but no difference in dwell time between the two tasks was detected at ID2. Simple main effect analysis of the Limb × ID interaction indicated that the dwell time for both limbs was longer at ID4 than ID2 (left-ID2 *M* = .018s, *SE* = .002s: left-ID4 *M* = .517s, *SE* = .103s; right-ID2 *M* = .018s, *SE* = .002s: right-ID4 *M* = .596s, *SE* = .105s). Simple main effect analysis of the Limb × ID interaction also indicated that the dwell time was longer for the right limb than left limb at ID4, but no difference in dwell time between the two limbs was detected at ID2. No other main effects or interactions were significant.

Percent time to peak velocity. The analysis of percent time to peak velocity detected a main effect of Task, $F(1, 14) = 5.57$, $p < .05$, and ID, $F(1, 14) = 12.06$, $p < .01$ (see Figure 18D). The PTPV for Task A (*M* = 48.28%, *SE* = 1.08%) was higher than for Task B (*M* = 44.85%, *SE* = .99%). The PTPV for ID2 (*M* = 49.44%, *SE* = .97%) was higher than for ID4 (*M* = 43.68%, *SE* = .91%). No other main effects or interactions were significant.

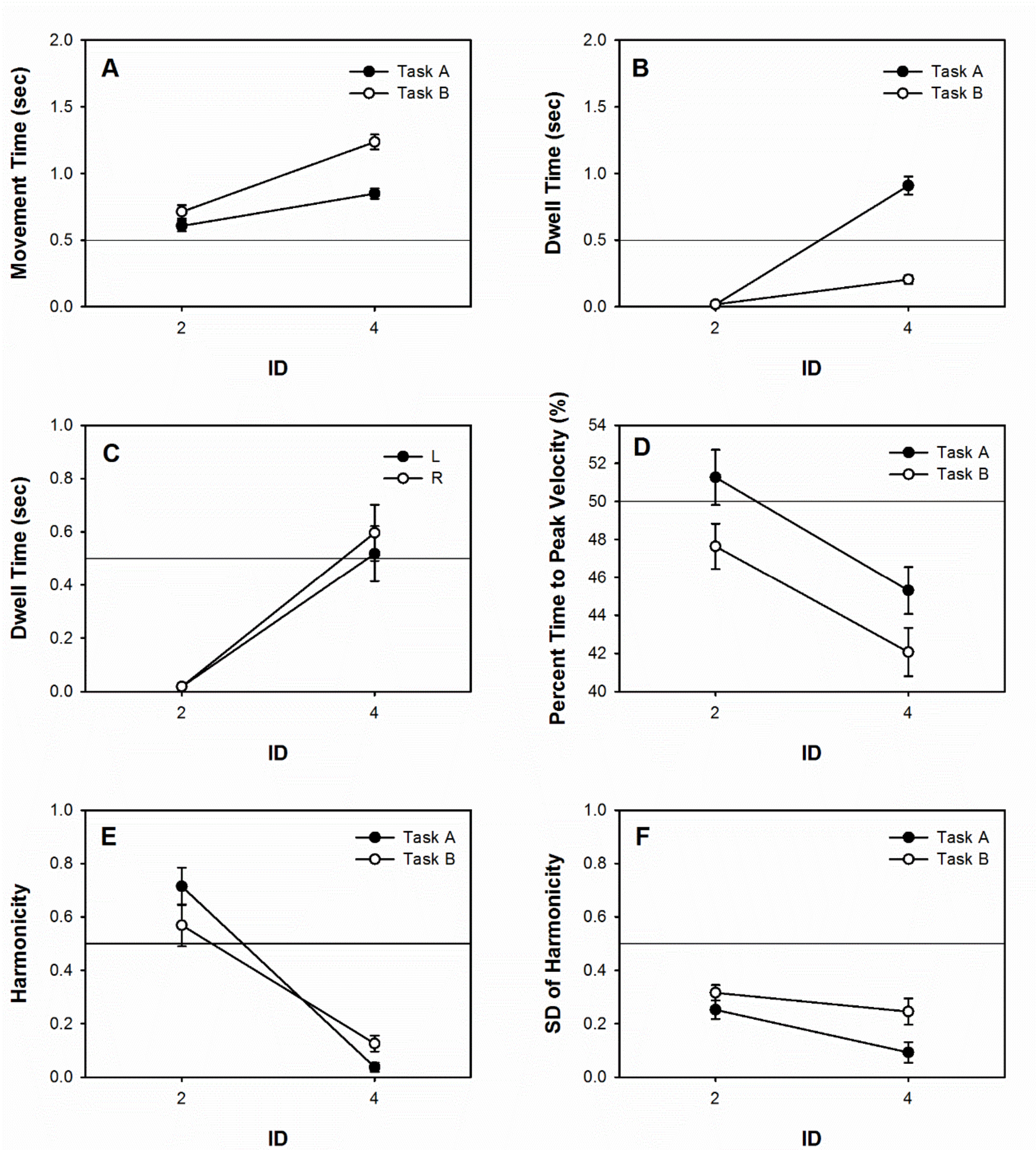

Figure 18. Mean movement time (A), dwell time (B, C), percent time to peak velocity (D), harmonicity (E), and harmonicity variability (F) for Task A and B as a function of ID. The error bars represent standard error.

Harmonicity (H). The analysis of harmonicity detected a main effect of Limb, $F(1, 14) = 7.78$, $p < .05$, and ID, $F(1, 14) = 55.12$, $p < .01$ (see Figure 18E). The H values for the left limb ($M = .398$, $SE = .064$) were higher than for the right limb ($M = .324$, $SE = .063$). The H values for ID2 ($M = .641$, $SE = .054$) were higher than for ID4 ($M = .081$, $SE = .018$). No other main effects or interactions were significant.

SD of Harmonicity (H). The analysis of standard deviation of harmonicity detected a main effect of Task, $F(1, 14) = 12.53$, $p < .01$ (see Figure 18F). The harmonicity variability for Task B ($M = .281$, $SE = .028$) was larger than Task A ($M = .172$, $SE = .029$). No other main effects or interactions were significant.

Discussion

The results suggest that even without previous experience with Lissajous displays participants were adept at adopting effective coordination strategies when faced with novel tasks and were also effective in altering this strategy when the size of the targets were increased or decreased. The bimanual coordination performance results for both Task A and B indicated that for the ID2 condition, participants moved the cursor in a circular path in the Lissajous display. The circular path resulted from participants adopting a bimanual control strategy with the two limbs moving in a 1:1 with a 90° phase offset. For Task A and B at ID2, relative phase was ≈ 90° with relatively small relative phase variability (<15°). This strategy could be considered very efficient because both limbs moved in a continuous cyclical fashion with very few adjustments observed in the displayed movement time series. In the ID4 condition where the target size was reduced, however, participants moved the cursor in more direct straight-line paths in the Lissajous display. For Task A, this resulted from the participants alternating between unimanual right and left limb movements. When tested on Task B, participants produced relatively discrete straight line movements between targets in the Lissajous plot with dwell times increased between movement segments.

CHAPTER V

GENERAL DISCUSSION AND CONCLUSION

General Discussion

Bimanual coordination and unimanual aiming are two of the most studied areas in motor learning and control research (see Elliott, Chua, Pollock, & Lyons, 1995; Shea, Buchanan, & Kennedy, 2015; Swinnen, 2002; Urbin, Stodden, Fischman, & Weimar, 2011, for reviews). However, these two areas of study have been combined in only a few experiments (e.g., Kelso et al., 1979a, 1979b). By manipulating the location and the size of targets in Lissajous displays, we combined the bimanual coordination tasks with Fitts aiming tasks to form bimanual aiming in three experiments. Experiment 1 involved unimanual (left and right limb) and bimanual aiming tasks with IDs of 3, 4, 5, and 6 in an ID increasing or ID decreasing order between trials; Experiment 2 also involved unimanual and bimanual aiming tasks with IDs of 2.5 to 6.0 in 0.5 increments or with IDs of 6.0 to 2.5 in 0.5 decrements within a trial. The smaller ID increments or decrements in Experiment 2 were included to more precisely determine the critical ID (ID_c) under increasing and decreasing ID conditions. In Experiment 3, one task (A) was designed so that the participant could complete the task using either unimanual or bimanual coordination strategy. The second task (B) was designed so that participants could complete the task using relatively simple or more difficult bimanual coordination strategies. Both tasks in Experiment 3 required the limb(s) to move with IDs of 2 or 4. The design of bimanual aiming tasks in the three experiments allows us to use continuous bimanual coordination measurements (i.e., relative phase, relative phase variability) to investigate the bimanual aiming movements and use unimanual measurements to determine the differences, if any, in the control processes used in bimanual and unimanual (left and right limb) aiming. The bimanual coordination literature has demonstrated that more difficult bimanual coordination patterns (e.g., 1:1 bimanual coordination patterns with a 90° phase offset, multi-frequency coordination patterns) often result in a less stable coupling than the less difficult in-phase or anti-phase coordination patterns. The unimanual aiming literature has demonstrated that increases in task ID result in changes in the unimanual control strategies used to perform the task (Buchanan et al., 2006; Guiard, 1997; Meyer et al., 1988). However, little is known about how changes in this type of constraint affect the changes in control strategies in bimanual aiming tasks and in left (non-dominant) limb movement.

The results of Experiment 1 and 2 indicated that when the accuracy requirements were increased mean relative phase values became closer to 0 while relative phase variability remained similar across IDs indicating that increasing the accuracy requirement resulted in reduced relative phase bias but not more stable coupling between the two limbs (see Table 1). The bimanual results of Experiment 3 suggest that participants were adept at adopting effective coordination strategies when faced with novel experiment tasks and were also effective in altering this strategy when the size of the targets were increased or decreased. The control processes used in bimanual aiming tasks of all three experiments appear to be similar to the changes in the kinematic features of the movement time series observed in unimanual tasks as the ID is increased or decreased. The end-effectors' motion switched from a cyclical motion to a discrete motion as ID increased and switched from discrete to cyclical motion as the ID was decreased.

Control strategies — bimanual and unimanual

The bimanual coordination literature has consistently argued that bimanual control is in many situations relatively more difficult than unimanual control especially when the task requires the two limbs to activate non-homologous muscles and/or produce different movement patterns (Kelso et al., 1979a, 1979b). The primary purpose of all three experiments was to determine whether the control strategies used to perform reciprocal bimanual aiming tasks are similar to those used in discrete and reciprocal unimanual aiming tasks (Buchanan et al., 2006; Guiard, 1993, 1997; Kelso et al., 1979a, 1979b). Note that the present experiments utilized Lissajous displays, in which the position of both limbs was integrated into a single position. In the bimanual conditions, both limbs were required to simultaneously achieve the target areas in order to "hit" the target (Shea et al., 2012). In all three experiments, the kinematic measures suggest that the control strategies utilized in the bimanual aiming tasks are similar to those used in discrete and reciprocal unimanual aiming tasks (Buchanan et al., 2006; Guiard, 1993, 1997; Kelso et al., 1979a, 1979b). That is, regardless of whether performances were tested in a decreasing or increasing ID condition, movement time, DT, and cycle duration were increased, and PTPV was reduced at the higher IDs indicating that more percentage of time was spent in the deceleration phase. In addition, the H value was reduced as the ID was increased. The performance results for both Tasks A and B in

Experiment 3 also indicated that as ID increased segment movement times (time between two targets) were slower and hit numbers were decreased. These kinematic features all indicated that as ID increased, the end-effectors' motion gradually switched from cyclical motion to discrete motion. These changes in kinematic control strategies as influenced by ID in all three experiments are consistent with Buchanan et al. (2006) and Guiard (1993, 1997) unimanual aiming studies. However, at specific ID conditions there were also some differences in kinematic control between bimanual and unimanual aiming tasks.

The significant Manual × ID interactions were found in DT and SD of H analyses in both Experiment 1 and 2. Simple main effect analysis of the Manual × ID interaction in dwell time data indicated that both limbs dwelled at the targets longer in the bimanual than for the unimanual condition at higher IDs (see Figure 9E, H and Figure 13D, H), although the right limb generally dwelled at the targets longer than the left limb. Significant Manual effect was also found in MT analysis in Experiment 2. When target width scaling occurred within a trial, the bimanual aiming resulted in longer movement time than unimanual aiming at all IDs. This may indicate that the bimanual aiming task requires more processing demands than the unimanual aiming task, especially at higher ID conditions.

The H values in Experiment 1 for both the bimanual and unimanual tasks crossed the H = 0.5 threshold in the interval between ID = 4 and ID = 5, however, the H values in Experiment 2 for both the unimanual tasks crossed the H = 0.5 threshold in the interval between ID = 4 and ID = 5 but for the bimanual task crossed the tasks crossed the H = 0.5 threshold in the interval between ID = 3 and ID = 4. The H values indicate the transition from cyclical to discrete actions (and vice versa) occurred in the region of $3<ID<5$. The transition region for bimanual aiming observed in Experiment 1 is consistent with the ID_c region ($4<ID<5$) found in previous unimanual aiming tasks (Buchanan et al., 2006; Guiard, 1997) but the transition region for bimanual aiming observed in Experiment 2 occurred at relatively lower ID_c region ($3<ID<4$). The H data results indicated that the ID_c for bimanual aiming was lower than the ID_c for unimanual aiming, and the difference between the bimanual and unimanual ID_c regions was larger when target width scaling occurred within a trial. Probably, constantly changing IDs causes participants taking in more motor resources for bimanual than unimanual aiming resulting in a tendency of using relatively slower discrete control strategies.

A significant Manual × ID interaction was also found in the harmonicity variability data in Experiment 1 (see Figure 9H) and Experiment 2 (see Figure 13H). The harmonicity variability data for both the bimanual and unimanual conditions and the ID conditions demonstrated an inverted U-shape relation. That is, the harmonicity variability values increased, plateaued, and then decreased, when the ID was increased or decreased. The enhancement of fluctuations for the unimanual task was approached from both the above ($IDs<ID_c$) and below ($ID_c<IDs$) directions, which is consistent with the findings in the Buchanan et al. (2006) study. However, the decrease in the harmonicity variability for the bimanual condition occurred at lower ID condition (i.e., ID4 in Experiment 1 and ID3 in Experiment 2) than the unimanual condition (i.e., ID5 in Experiment 1 and ID4 in Experiment 2). This increase and then decrease in the

harmonicity variability is consistent with the idea of the limb's motion underwent a loss of stability and the occurrence of enhancement of fluctuation (Buchanan et al., 2006). Studies have shown that loss of stability is a key mechanism underlying pattern change (Byblow, Carson, & Goodman, 1994; Carson, Goodman, Kelso, & Elliott, 1995; Kelso, 1995; Kelso et al., 1986; Schoner et al., 1986; Schoner & Kelso, 1988). In other words, the harmonicity variability data reveals the transition from cyclical to discrete control strategies occurred at lower ID condition for the bimanual than the unimanual condition. This may indicate that the discrete control strategy is more likely to be used in the bimanual aiming than the unimanual aiming under the same ID constraint. In addition, the transition of control strategies for both unimanual and bimanual aiming occurred at a lower ID when the IDs were systematically manipulated within a trial than between trials. Consistent with the H value data, the harmonicity variability data also indicate that bimanual control was more difficult than unimanual control and that an aiming task that requires constantly changing ID (target size) within a trial is more difficult than aiming tasks that involves ID changing between trials.

Control strategies — unimanual left-limb and right-limb

The second purpose of Experiments 1 and 2 was to determine if unimanual left and right limb control differed as ID was increased or decreased. Note that while there is a very large aiming literature the majority of the literature involves the dominant right limb. Thus, it is important to determine whether the control of the left and right limb are similar as ID is increased or decreased. A significant limb effect or any interaction associated with limb were not detected for movement time and percent time to peak velocity indicating that the unimanual control strategies utilized for the left-limb aiming tasks were similar to the control strategies used for the right-limb aiming tasks. However, differences were only detected in dwell time in Experiment 1 and in the H data in Experiments 1 and 2. In Experiment 1, the dwell time for the left limb was slightly shorter than that for the right limb. In both Experiments 1 and 2, the H value for the left limb was slightly higher than that for the right limb, which may indicate an asymmetric coupling in the bimanual aiming. Asymmetric coupling has been shown to be relevant to handedness. Asymmetric amplitude bimanual studies have indicated that, when right handed participants performing the larger amplitude movement, the non-dominant left limb tended to undershoot to a lesser extent compared to the dominant right limb (Marteniuk et al., 1984; Sherwood, 1994; Spijkers & Heuer, 1995). Recent studies also indicate that disparity in movement amplitude may influence the lead-lag relationship between limbs, where the limb produces smaller amplitude tends to lead in time the limb performing the larger amplitude, and this lead-lag relation, although slight, may systematically shift the coordination pattern away from the intended coordination pattern (Buchanan & Ryu, 2006). Amazeen, Amazeen, Treffner, & Turvey (1997) have also provided evidence for handedness-related lead asymmetry in a 1:1 bimanual coordination task with left-handed participants tending to lead with their left hand while right-handed participants tended to lead with their right hand. The asymmetric coupling in dwell time and H values in Experiment 1 is consistent with Amazeen et al. (1997) study. While participants were performing 1:1 bimanual aiming with equal amplitude, the dominant right limb tended to lead the coupling by decelerating earlier than the non-dominant left limb but accelerate at the same time with the non-dominant left limb for the next aiming segment, which resulted in a longer dwell time and smaller H values for the dominant limb.

Control strategies — influence of order of presenting ID and critical ID

The last purpose of Experiment 1 and 2 was to determine whether order of presenting ID (i.e., increasing or decreasing ID order) influences the control strategies utilized in bimanual and unimanual aiming tasks. Significant Order × Manual interaction was not detected in any dependent variables indicating that the order of presenting ID influences the control strategies utilized in bimanual and unimanual aiming tasks in a similar manner. Significant Order × ID interactions were found in the movement time and percent time to peak velocity analyses. Simple main effect analysis of the Order × ID interaction in the movement time data indicated that the motion was slower in the decreasing ID order compared to the increasing ID order at the higher IDs (see Figure 9D and Figure 13C). Note that the analysis of dwell time failed to find an Order effect or any interaction effect involving Order indicating the order of presenting ID influences the movement time but not dwell time. This finding is consistent with the Buchanan et al. (2006) study which also showed that the movement time was significantly longer in the ID decreasing condition compared to the ID increasing condition at higher IDs (ID = 4.94 and ID = 5.91). The more difficult/higher ID task was influenced more by this order effect compared to the less difficulty/lower ID task. Similarly, participants' control strategy may also get influenced by the trials they practice before and may be inclined to maintain the same percent time to peak velocity as the previous ID, resulting in a tendency of maintaining a slightly higher PTPV in the ID increasing order or/and a slightly lower PTPV in the ID decreasing order. The fact that a flat slope in the increasing ID order and a steep slope in the decreasing ID order outside the ID_c region ($4<ID<5$) in the Order × ID interaction plot (Figure 9F and 13E) confirms my prediction. It is possible that the enhancement of fluctuation at the ID_c region ($4<ID<5$ in Experiment 1 or $3<ID<5$ in Experiment 2) interferes with the order effect.

Control strategies — providing a choice of control strategy

Experiment 3 provided participants opportunities to choose between different unimanual and bimanual control strategies or to choose between more stable and more difficult bimanual coordination strategies. The results suggest that participants were adept at adopting effective control strategies when faced with novel tasks and were also effective in altering this strategy when the size of the targets were increased or decreased. The bimanual coordination performance results for both Task A and B indicated that for the ID2 condition, participants moved the cursor in a circular path in the Lissajous display. The circular path resulted from participants adopting a bimanual control strategy with the two limbs moving in a 1:1 with a 90^o phase offset. For Task A and B at ID2, relative phase was ≈ 90° with relatively small relative phase variability (<15°). This strategy is similar to that portrayed using simulated data in Figure 15 (A,C,E and G,I,K).

In the ID4 condition where the target size was reduced, however, participants moved the cursor in more direct straight-line paths in the Lissajous display. For Task A this resulted from the participants alternating between unimanual right and left limb movements. When tested on Task B, participants achieved the relatively straight line movements between targets by alternating between in-phase (moving the limbs in the same direction) and anti-phase (moving the limbs in opposite directions). These control strategies are also similar to those depicted in Figure 15 (B,D,F and H,J,L) using simulated data.

Note that for Tasks A and B for the ID4 conditions that mean relative phase values were also ≈ 90°. However, this was not a result of participants adopting the same control strategy used in the ID2 conditions, but rather this was a result of participants performing Task A-ID4 by alternating between left and right limb unimanual control strategies where the one limb was not moving while the other limb was moving. This results in relative phase values changing when the phase angle of one limb does not change while the phase angle of the other limb is changing. The result was a substantial increase in relative phase variability from $<15^{o}$ for the ID2 condition to 46^{o} for the ID4 condition. For Task B, mean relative phase was also similar across IDs, but relative phase variability only modestly increased as the ID increased. The data indicated that participants performing Task B–ID4 continually transitioned between bimanual in-phase and anti-phase coordination patterns at the ID4 condition. Note also that the relative phase computation for the ID4 condition was influenced by not only the fact that the limbs transitioned between moving in the same direction and moving in opposite directions, but also the finding that the limbs were offset in terms of where the phase cycle for one limb started and ended and where the phase cycle for the other limb started and ended. This produced relative phase values that were less variable than for Task A-ID4.

Taking the bimanual and unimanual measures of performance results together, we conclude that at the low ID condition participants when performing Tasks A and B produced a continuous 90° bimanual coordination pattern (Figure 16A,O) with relatively harmonic movements for both limbs. The movement for each limb is consistent with reciprocal unimanual movement typically observed under low ID constraints. However, in the ID4 condition, the participants chose to switch between unimanual left and right movements in Task A (Figure 16B,I) and to switch between 1:1 in-phase and anti-phase bimanual coordination patterns in Task B (Figure 16P,W). The present results suggest that participants when facing different task restraints (e.g., target arrangement and target size) chose different unimanual and bimanual control strategies. When asked to perform Task A-ID2, participants choose a more difficult and presumably less stable 1:1 bimanual coordination pattern with 90° relative phase over a less difficult unimanual control strategy, but chose the less difficult and more stable unimanual control option when the ID was increased. This finding, in part, goes against our initial prediction based on the bimanual coordination literature. The literature suggests that more stable bimanual coordination patterns are preferred over less stable bimanual coordination patterns and unimanual control strategies are preferred over bimanual control strategies when permitted by task constrains. When asked to perform Task B-ID2, participants also chose a continuous bimanual 1:1 with 90° relative phase coordination patterns, but also utilized a slightly modified form of this control strategy when the ID was increased.

Perhaps most striking was the finding that all participants adopted approximately the same control strategy for each of the task conditions with the strategy not influenced by which ID condition was tested first or second.

The difficulty in producing 1:1 bimanual coordination patterns with various phase offsets has been attributed, in part, to phase attraction to the intrinsic dynamics (in-phase or anti-phase) of the perceptual-motor system (e.g., DeGuzman & Kelso, 1991; Kelso & DeGuzman, 1988; Peper, Beek, & van Wieringen, 1995; Treffner & Turvey, 1993). These characteristics have been formally characterized (e.g., Kelso, 1995), extensively investigated (e.g., Carson, 2005; Ivry, Diedrichsen, Spencer, Hazeltine, & Semjen, 2004, for reviews), explained using concepts taken from nonlinear dynamical systems and modeled using nonlinearly coupled limit cycle oscillators (Haken et al., 1985) perturbed by stochastic forces (Schoner et al., 1986).

Indeed, the learning of many phase relationships other than in-phase and anti-phase have required several days of practice and some more difficult multi-frequency bimanual coordination patterns have been deemed impossible to be effectively performed without very extensive practice. However, when integrated information such as provided in Lissajous displays are used, as in the present experiments, participants' performance on a wide variety of phase relationships and multiple frequency ratios have been shown to be remarkably stable after only a few minutes of practice (e.g., Kovacs et al., 2010a, 2010b). Similarly, this literature has demonstrated that participants can intentionally transition between various phase relationships and even transfer from one difficult frequency ratio (5:3) to another (4:3) without warning or additional practice suggests that the effects of the intrinsic dynamics are minimized when this type of feedback is provided. Indeed, in each of these experiments relative phase errors were not only similar across the tasks, but also remarkably low (variability ≈ 10º). We argue that this was possible because salient, unified extrinsic information was provided in the form of a Lissajous display. This perceptual information allowed participants detect and correct coordination errors allowing them to rapidly "tune-in" the required behavior. It is important to note that other forms of integrated displays have also produced very positive results (e.g., Boyle et al., 2012; Preilowski, 1972; see Shea et al., 2016, for review) and are sometimes used in game controls to integrate the movement of the fingers of the left and right limb or more natural situations (Diedrichsen, Nambisan, Kennerley, & Ivry, 2004).

In terms of the Experiment 3, it is truly remarkable that participants, although not previously exposed to this form of feedback, were able to choose very effective control strategies to complete the specific task requirement and then alter the their control strategy as the ID was increased or decreased depending on the order in which they practiced the ID conditions. The bottom line is that participants find it relatively easy to traverse the attractor landscape when integrated feedback is provided. Thus, when feedback is provided that directs the attention of the participant to the integrated movement of their limbs, the pool of salient control options are greatly increased. The ability to quickly and effectively modify newly developed coordination strategies demonstrates the amazing capabilities of the perceptional motor system.

Conclusion

In sum, increasing the accuracy requirement results in the end-effectors motion switching from cyclical to discrete control strategies as ID is increased and from discrete to cyclical as ID is decreased for both unimanual and bimanual aiming tasks, and for both limbs. The harmonicity data that captured the transition between control strategies revealed that as the accuracy requirement increases the transition for the bimanual aiming tasks occurred at lower IDs than the unimanual aiming tasks and for the bimanual aiming with a sequence than without a sequence. In terms of bimanual coordination, increasing the accuracy requirement resulted in a tighter but not more stable coupling between the two limbs. When participants were provided a choice of performing unimanual and bimanual control strategies in more difficult bimanual sequential aiming tasks, they were able to select and effectively implement appropriate unimanual and bimanual control strategies depending on the demands of the task. The findings suggest that the unimanual and bimanual control strategies in bimanual and unimanual aiming are determined by accuracy requirements. Note that the bimanual aiming tasks of the present study utilized same-size targets for each ID task. Future extensions of the present study should consider examination of more difficult mixed-ID bimanual aiming that involves transitions between different-size targets.

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