

Attention Demands across Extended Practice of a Bimanual Coordination Task

by

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ABSTRACT

Five experiments were conducted, the overall purpose of which was to examine the effects of practice on attention demands of a new bimanual coordination task. In Experiments 1-3 participants received 1, 000 trials to learn a 90° out-of-phase task. The secondary task from which attention demands were derived was probe reaction time (probe-RT). Although cognitive demands decreased with practice, results showed that performance of the 90° pattern continued to demand attention, even after extended practice. Similar results were found in Experiment 4 when examining the attentional costs of performing naturally occurring coordination tendencies (i.e., in-phase, anti-phase). These findings indicate that a minimal level of cognitive control is required for the execution of newly acquired bimanual coordination tasks, as well as for the performance of intrinsic coordination biases.

These experiments also examined the influence of continuous on-line visual feedback on learning and attention demands. Individuals received concurrent visual feedback for 65% of each practice trial (Experiment 1) or for only 35% of each trial (Experiment 2). Results showed that participants were highly successful at producing the required task when visual feedback was available, but were less able to inhibit the influence of pre-practice biases whenever visual feedback was unavailable to guide performance. Experiment 3 examined the influence of manual guidance on performance of the 90° pattern under limited conditions of visual feedback. When participants' limbs were physically moved through the required movement via servo torque motors individuals were better able to break away from pre-existing tendencies. Finally, Experiment 5 revealed that probe-RT was slower when performing in the absence of visual feedback, in comparison to its presence. Attentional requirements also increased whenever the dominant source of feedback was changed within a trial, although adding visual feedback to the perceptual display resulted in only a temporary increase in probe-RT. In addition to examining the attention demands of bimanual coordination, these investigations highlight the importance of exploring instructional strategies that reduce the negative effects of pre-existing behavioural tendencies on the learning of new complex motor tasks.

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In Loving Memory
of



Cecil Douglas Bredin
December 31st, 1920 – November 10th, 2003

OVERVIEW OF DOCUMENT

The following dissertation consists of five experiments, presented in Chapters 1 through 5, respectively. In these experiments, attention demands and bimanual coordination were examined, as well as the effects of manipulating availability of continuous on-line visual feedback and the influence of manual guidance for learning new coordination skills. Chapter 6 provides an overview of the findings reported in this thesis focusing discussion on theoretical issues surrounding attention demands and skilled motor performance. Finally, two appendices are included. Appendix A is an extensive review of literature, which sets the groundwork for topics discussed in the present line of investigations. Some readers may elect to read the review of literature first. Appendix B presents a sixth study conducted with fellow colleagues that was directly relevant to the aforementioned studies. This final experiment examined methodological procedures used to assess learning of a bimanual coordination pattern.

STATEMENT OF ETHICS

All experiments conducted in this dissertation were carried out according to the ethical guidelines set by the University Behavioural Science Screening Committee at the University of British of Columbia for research involving human participants.

CHAPTER I

EXPERIMENT 1

Attention Demands and the Effects of Continuous On-Line Feedback during Extended Practice of a Bimanual Coordination Task

Introduction

In numerous everyday activities individuals are required to produce more than one goal-related task at the same time. Unfortunately, performing two tasks concurrently can prove difficult and the quality of performance is often less than if each task had been performed alone. Explanations for this common occurrence are often based on resource theories of attention, which postulate the existence of an inherent limited pool (or pools) of processing capacity (e.g., Kahneman, 1973; Navon & Gopher, 1979; Wickens, 1980, 1984). According to this perspective, some (or even all) of the limited processing resources are drawn upon or allocated to the performance of a task. Moreover, this limited resource capacity may be partitioned in a flexible and voluntary manner if the simultaneous performance of two or more events is required. When two concurrent tasks use the same resource pool and the joint demands exceed the total capacity of available resources, a decrement incurs in one of, or in both of, the simultaneously performed tasks. Referred to as dual-task interference, any improvement in performance on one task comes at the expense of performance on the other task (e.g., Kahneman, 1973; Norman & Bobrow, 1975) (*Refer to Appendix A-The Study of Divided Attention*).

One captivating position of this theoretical perspective of attention concerns the effects of practice. A number of investigations have shown that the concomitant performance of two or more tasks can be substantially improved upon as a function of practice (e.g., Spelke, Hirst, & Neisser, 1976), and this capability may be a necessary aspect of expert levels of performance (Abernethy, 1993). According to capacity sharing theories, extended practice on a task leads to 'automaticity'. One perspective, referred to as the modal view (see Logan, 1988, 1992), defines automaticity as processing without attention, whereby practiced operations no longer impose demands on a system's resources for task execution. Performance

proceeds without the voluntary allocation of attention to various task components (Laberge & Samuels, 1974; Schneider & Shiffrin, 1977) and mental operations function without experiencing interference from, or generating interference with, ongoing processing activities of concurrent tasks (Pashler, 1998). In essence, practice permits the development of the ability to bypass attention (e.g., LaBerge & Samuels, 1974; Shiffrin & Schneider, 1977) with the underlying assumption that more practice on a task leads to more automaticity (Brown & Bennett, 2002)(*Refer to Appendix A – The Relation between Attention and Automaticity*).

Although the acquisition of automaticity is operationally interpreted as the gradual withdrawal of attention, it is generally accepted that complete elimination of dual-task interference is not necessary to demonstrate automatic processing. Rather, evidence of automaticity is taken whenever there is a significant decrease in dual-task interference following practice of a task (Brown & Bennett, 2002). In recent years, researchers have begun questioning whether elimination of dual-task interference is actually achievable, as suggested in the basic theoretical tenets of a capacity perspective (see Pashler, 1998), even after extended periods of practice (e.g., Ahissar, Laiwand, & Hockstein, 2001; Blischke, 1998). In contrast, even well practiced motor tasks operating at consistently high levels of excellence are postulated to demand attention. This idea is examined in the present experiment, whereby the primary purpose was to investigate the effects of practice on attention demands and dual-task interference across the extended acquisition of a novel motor task.

Skilled Motor Behaviour

The association between extended practice and the notion of automaticity is a central tenet in traditional theories of motor skill acquisition, which assume that learning progresses in phases that can be differentiated on the basis of the cognitive activity associated with the production of the response (e.g., Adams, 1971; Fitts & Posner, 1967). As learning progresses from an inexperienced to skilled state of behaviour, it is understood that a shift occurs from the conscious and deliberate allocation of attention to the use of automatic processes. Diminishing demands on

attention are advantageous to the performer in that processing load is reduced, thereby permitting the individual to focus on higher-order aspects of performance (*Refer to Appendix A – Representational-Based Accounts of Skill Acquisition*).

Despite these theoretical claims, studies examining the acquisition of novel motor tasks rarely include periods of prolonged training. One reason for this lack of empirical foundation is that investigating the acquisition of a complex motor task mandates extended observation before an individual begins to approximate high degrees of task proficiency. Therefore, the amount of practice trials typically employed in learning studies have been limited, constraining investigation to the early acquisition stages of the learning process (see Adams, 1987, for a review). Recognizing the limitations in studying novices, a more recent descriptive approach has been to compare the characteristics of performers at various levels of skill. However, the limitation of protocols using highly skilled performers or novice-expert comparisons is that it only identifies discriminative factors between skilled and less skilled performers, prohibiting inferences as to the cause of these differences. Although many factors have been investigated using this approach – the recall of briefly presented information (e.g., Allard, Graham, & Paarsalu, 1980), visual search patterns (e.g., Savelsbergh, Williams, van der Kamp, & Ward, 2002), cue recognition within the environmental display (e.g., Abernethy & Russell, 1987) – the manner in which skilled and less skilled performers allocate attention for the execution of a task, especially as it unfolds in real-time, has yet to be adequately examined (Beilock, Carr, MacMahon, & Starkes, 2002). Taking these ideas together, the evolution of attentional mechanisms across the acquisition of a complex motor task has received little focus, and is not well understood.

Assessing Attention Demands

One way to assess attention demands of a given task is to employ a secondary-task paradigm. This approach is based on having participants perform two tasks concurrently – a basic task, which is referred to as the primary task, and a secondary task. The primary task is the task for which attention demands are assessed, while performance on the secondary task is used to infer the attention

demands required by the primary task. In the secondary-task paradigm, participants are instructed to maintain a given level of primary task performance during the concurrent performance of the second task. If poor performance is displayed on the secondary activity, it is generally assumed that a large proportion of information-processing capacity has been allocated to the primary task to maintain an acceptable level of performance. The more demanding a primary task is the greater proportion of attentional capacity is required for task execution. Therefore, at early stages of learning, secondary task performance should be relatively poor since it is postulated that the primary task demands a large portion of the learner's processing capacity. After an extended period of task-specific practice, secondary task performance should become relatively unimpaired because primary task demands have diminished. Eventually, the secondary task should be performed just as well under dual conditions, as performed alone. The absence of any single-to-dual task decrement in secondary task performance is assumed to indicate that the primary task is performed 'automatically', requiring little or none of the performer's attentional capacity (for reviews of dual-task methodology, see Abernethy, 1988, 1993) (*Refer to Appendix A – Assessing Attention Demands*).

To examine attention demands across the time course of learning, we asked individuals to learn a continuous bimanual coordination movement. The secondary task, from which attention demands of the primary task were derived, was the classic measure of discrete reaction time (RT). In the dual-task condition, participants were instructed that attentional priority should be given to the bimanual coordination task such that the secondary task does not interfere with the primary task even if performance on the RT task decreases.

Bimanual Coordination

In recent years, there has been a trend towards examining more complex, coordinative skills. An advantage of this approach is that these skills are thought to be more representative of real-world motor learning environments (e.g., Hodges & Lee, 1999). Moreover, recent research has shown that the study of interlimb

coordination provides a useful framework with which to investigate the acquisition of new motor skills.

In studies of bimanual coordination (i.e., requiring concurrent activities of the left and right limb), inherently stable (or preferred) coordination patterns have been identified: a strong symmetrical in-phase relationship and a somewhat weaker anti-phase limb relationship (Kelso, 1984). During in-phase (0° of relative phase), the limbs are coordinated to be in the same phase of the cycle at the same time. That is, in-phase coordination refers to the simultaneous contraction of homologous muscles, which requires the limbs to flex and extend in synchrony. In contrast, the limbs are in the opposite phase of the cycle at the same time during anti-phase performance (180° out-of-phase). The limbs flex and extend in alternation because of the simultaneous activation of nonhomologous muscle groups. Both in-phase and anti-phase coordination are thought to be intrinsic to the system, and can be performed skilfully, without practice (Cohen, 1971; Kelso, 1984; Tuller & Kelso, 1989; Yamanishi, Kawato, & Suzuki, 1980). However, with practice, recent research has shown that less intrinsic patterns of coordination can emerge as additional, relatively stable patterns, against the backdrop of pre-existing coordination tendencies (e.g., Fontaine, Lee, & Swinnen, 1997; Lee, Swinnen, & Verschueren, 1995; Swinnen, Lee, Verschueren, Serrien, & Bogaerds, 1997; Wenderoth & Bock, 2001; Zanone & Kelso, 1992; 1997) (*Refer to Appendix A – Motor Dynamics: Fundamental Concepts and Terminology, as well as Motor Learning and Dynamic Pattern Theory*).

One of the most common to-be-learned patterns utilized to-date has been the 90° relative phase (RP) pattern. To perform this pattern, participants must learn to coordinate the limbs with an offset of 90° between the limbs, whereby one limb leads the other by a quarter of a cycle. This pattern has received considerable attention within the literature because it is considered to be an unstable point half-way between the stable attractor states of in- and anti-phase (Zanone & Kelso, 1992). The difficulty with learning a 90° out-of-phase pattern is that there is a tendency for the individual to be drawn to the more stable pre-existing coordination pattern of anti-phase, or (less frequently) the in-phase pattern of coordination. However, as learning progresses, the tendency to perform an intrinsic motor pattern diminishes

and is replaced by an increased attraction to the criterion pattern (e.g., Lee et al., 1995; Swinnen et al., 1997). Therefore, practice leads to the evolution and stabilization of the required 90° pattern, which involves a relatively permanent change in the pre-existing coordination dynamics of a system towards an attractor layout that incorporates the new phasing pattern (see Zanone & Kelso, 1992).

The provision of relative motion feedback has been shown to be a powerful source of information for the acquisition of the 90° out-of-phase task (Lee et al., 1995; Swinnen et al., 1997). However, it remains unclear whether or not individuals become increasingly dependent on this visual information source as learning progresses. Proteau and colleagues (e.g., Proteau, Marteniuk, Girouard, & Dugas, 1987) have provided evidence, which suggests that afferent information sources, especially vision, become increasingly important for motor performance as a function of practice. This view postulates that a single source of afferent input is quickly identified early in learning as optimal, and progressively dominates other information sources during the time course of learning (Tremblay & Proteau, 1998). A corollary of this perspective suggests that movement learning is relatively specific to the sources of information under which practice occurs. If a dominant source of information is withdrawn at later stages of acquisition, performance deteriorates because the individual no longer has a reliable source of reference with which to support his or her performance (see Proteau, 1992, for a review of early work; see Proteau & Isabelle, 2002 for an example of more recent work). Therefore, a secondary purpose of this investigation was to manipulate the provision of relative motion feedback during performance to determine its relative contribution to the acquisition and transfer of coordination skills. More specifically, we were interested in examining whether a specificity of learning effect would also be evident when learning a 90° out-of-phase task across extended practice.

Overview of Experiment

In the present experiment, we examined how practice affected the production and stability of a bimanual coordination task corresponding to a 90° out-of-phase pattern (the primary task). Participants engaged in ten sessions of 100 practice trials

per day across a two-week period (i.e., 1,000 practice trials). To facilitate acquisition of the 90° pattern, continuous on-line visual feedback was provided on a computer monitor. Specifically, displacement of the right limb resulted in horizontal movements on the computer screen, while displacement of the left limb resulted in vertical movements. Augmented feedback regarding current performance was displayed by plotting the real-time displacement of the right-limb on the ordinate against displacement of the left-limb on the abscissa. When the individual correctly moved his or her limbs in a 90° offset, the resulting plot (referred to as a Lissajous figure) appeared as a circle configuration on the monitor (e.g., Lee et al., 1995). Concurrent augmented feedback was available to participants for only the first ten seconds of each 13 s trial. Participants received no feedback for the final three seconds of the trial, followed by terminal feedback regarding the just-performed no-vision trial segment. Terminal feedback was also presented in the form of a Lissajous trace. Manipulating the provision of afferent information via occlusion allowed us to investigate the role played by vision across prolonged practice of a 90° bimanual coordination pattern.

To assess the individual's capability to perform the criterion task in an environment different from learning, participants were required to reproduce the 90° pattern without the use of on-line feedback immediately following 7 of the 9 acquisition sessions, and after a one-week retention interval. The final session was included to assess the extent to which post-practice changes in pattern accuracy and stability were retained across a period of no practice.

To determine the time course of attention demands across extended learning of the 90° task, participants were required to vocally respond to a computer-generated auditory signal on one-third of all practice and transfer trials (the secondary task). On probe trials, the auditory signal was either delivered during the vision segment of the trial or during the no-vision segment. This latter manipulation allowed us to investigate the relationship between attention demands and provision of visual sensory information across extended practice.

In the present experiment, it was hypothesized that practice would diminish attention demands of the 90° relative phase task, as measured by decreases in

reaction time of the secondary task above that when performed alone. A reduction in dual-task interference was predicted to occur following practice of the primary task, but a complete elimination of interference was not expected to emerge despite the extended and highly specific nature of practice. Early in learning, it was also postulated that participants would demonstrate considerable problems in producing the required 90° pattern. More importantly, at these initial stages, withdrawal of concurrent visual feedback was expected to cause a change (or drift) from the produced pattern towards a more intrinsically stable pattern of coordination (e.g., a drift towards an anti-phase pattern of coordination). At early stages of acquisition, we contend that vision is an important information source for learning the required limb phase relationship, especially considering the self-directed nature of the learning environment. Without vision, performance of this coordination pattern should be difficult to maintain prior to establishment of an attractor state at the criterion pattern. When the individual finally acquires the capability to perform a relative phasing of 90° with the limbs, stability of the produced pattern was expected to be maintained even upon withdrawal of relative motion feedback. However, if participants adopt a control strategy where vision is relied upon and processed to the detriment of other sensory sources during execution of the coordination pattern, its withdrawal is expected to have a debilitating effect on accuracy and stability of the required coordination pattern even at the later stages of learning.

Method

Participants

Informed consent was received from six self-professed right-handed individuals from a university population ($n = 5$ female; $n = 1$ male). The mean age of participants was 28.2 years ($SD = 7.7$, range = 23 - 43 years). All individuals were naïve to the purpose of the experiment and none had previous experience as a participant in a bimanual coordination investigation. Upon completion of the final session, all participants received remuneration. The experiment was carried out according to the ethical guidelines set by the University Behavioural Science Screening Committee for research involving human participants.

Primary Task and Apparatus

Participants were seated at a table facing a 14 in. colour monitor (Zenith flatscreen, ZCM-1490; VGA 640 x 480 pixels) with their forearms strapped comfortably into two angular manipulanda (Figure 1.1). The manipulanda were positioned such that the elbow joint was aligned with the axis of rotation and the hands were placed palm down on adjustable metal plates. The middle finger of each hand was placed between two vertical pins and secured by Velcro straps around the forearms and hands of the participant. The goal of the primary task was to learn how to correctly move the arms in the horizontal plane to produce a 90° RP pattern of coordination. When the limbs were correctly moved in 90° RP and with similar amplitudes, a circular pattern was produced on the computer monitor. Leading with the right-limb produced a circle pattern in a counter-clockwise direction, while a left-lead created a circle in a clockwise direction. The required amplitude of the movement for each arm was 40°, which corresponded to a 15 cm movement on the computer monitor. Feedback regarding movement amplitude was presented to participants via augmented computer feedback, as well as two table-top markers identifying the boundaries or maximal "IN" and "OUT" positions for each arm (Figure 1.1 – bottom right panel). Angular positions of the manipulanda were recorded using two optical encoders (Dynapar, E2025001303), one attached to the shaft of each manipulandum. Both optical encoders were connected to an interface card (Advantech Quadrature, PCI-833), giving a resolution of 10,000 counts per revolution. Angular position was sampled at a rate of 1000 Hz. An MS-DOS computer running custom software for data collection and analysis controlled the temporal events within each trial.

Secondary Task and Apparatus

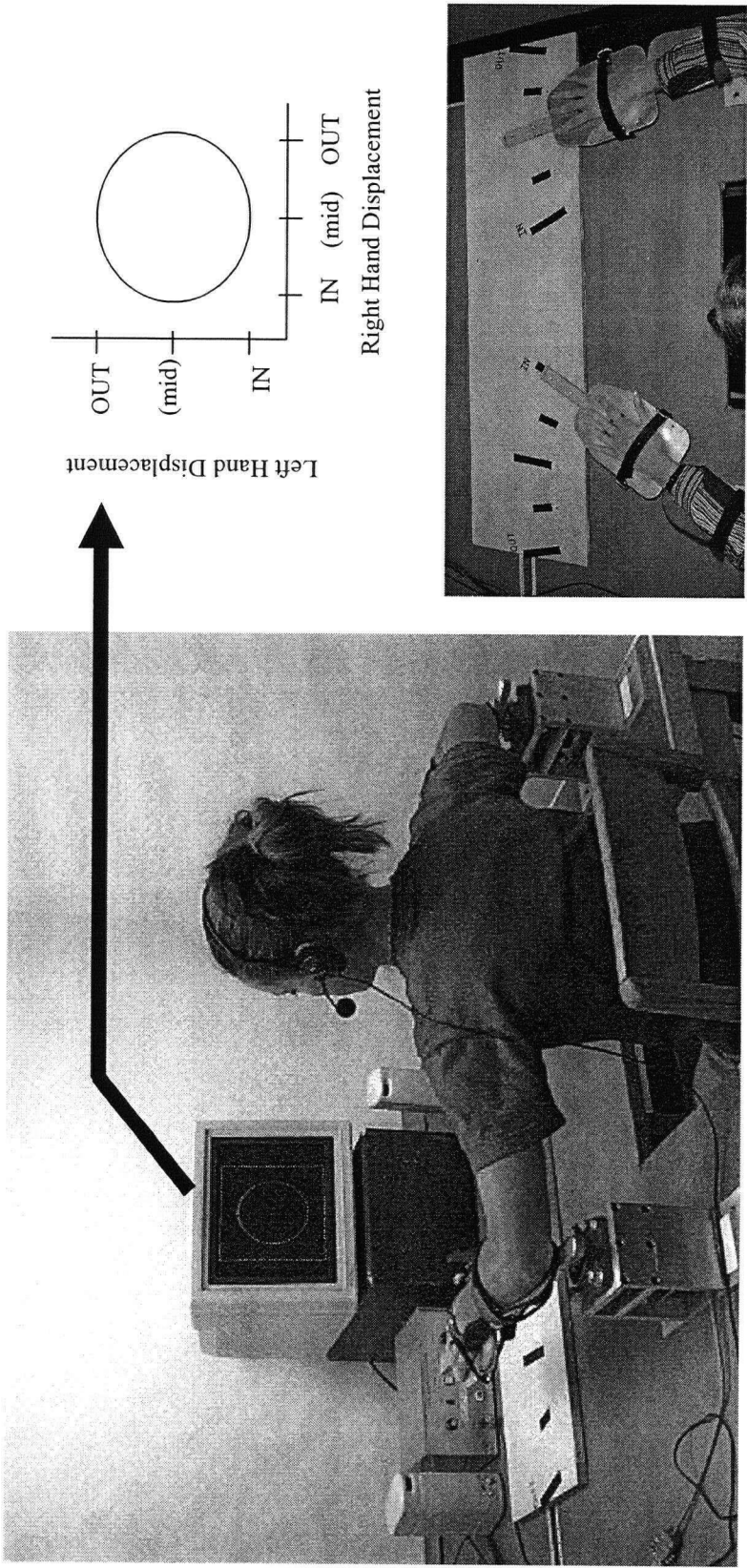
While performing the primary task, participants were required to emit a vocal response if at any time an auditory 'beep' occurred. The auditory signal was computer generated at 2000 Hz and was presented through a set of multi-media amplified speakers (EP-691 H) (Figure 1.1 - left panel). The duration of the auditory probe was 100 ms. A microphone (C-315 Labtec Headset/Boom microphone),

Figure 1.1. Apparatus and Experimental Set-Up.

(Left panel) Participants were asked to produce a 90° RP pattern of coordination by making continuous flexion and extension movements about the elbow joint in the horizontal plane. Producing a 90° RP pattern of coordination resulted in a circle pattern on the computer screen situated directly in front of the participant.

(Top right panel) A schematic diagram of the criterion circle pattern represented as a Lissajous figure.

(Bottom left panel) Amplitude boundaries were identified by two tabletop markers ("IN and OUT"), representing a required amplitude of 40° for each arm. When correctly moving the limbs in a 90° RP pattern of coordination, one limb will lag the other by a quarter of a cycle in time (e.g., when the participant's left limb is reversing direction at the "IN" marker, the right limb should be located midway between the "IN" and "OUT" boundary markers).



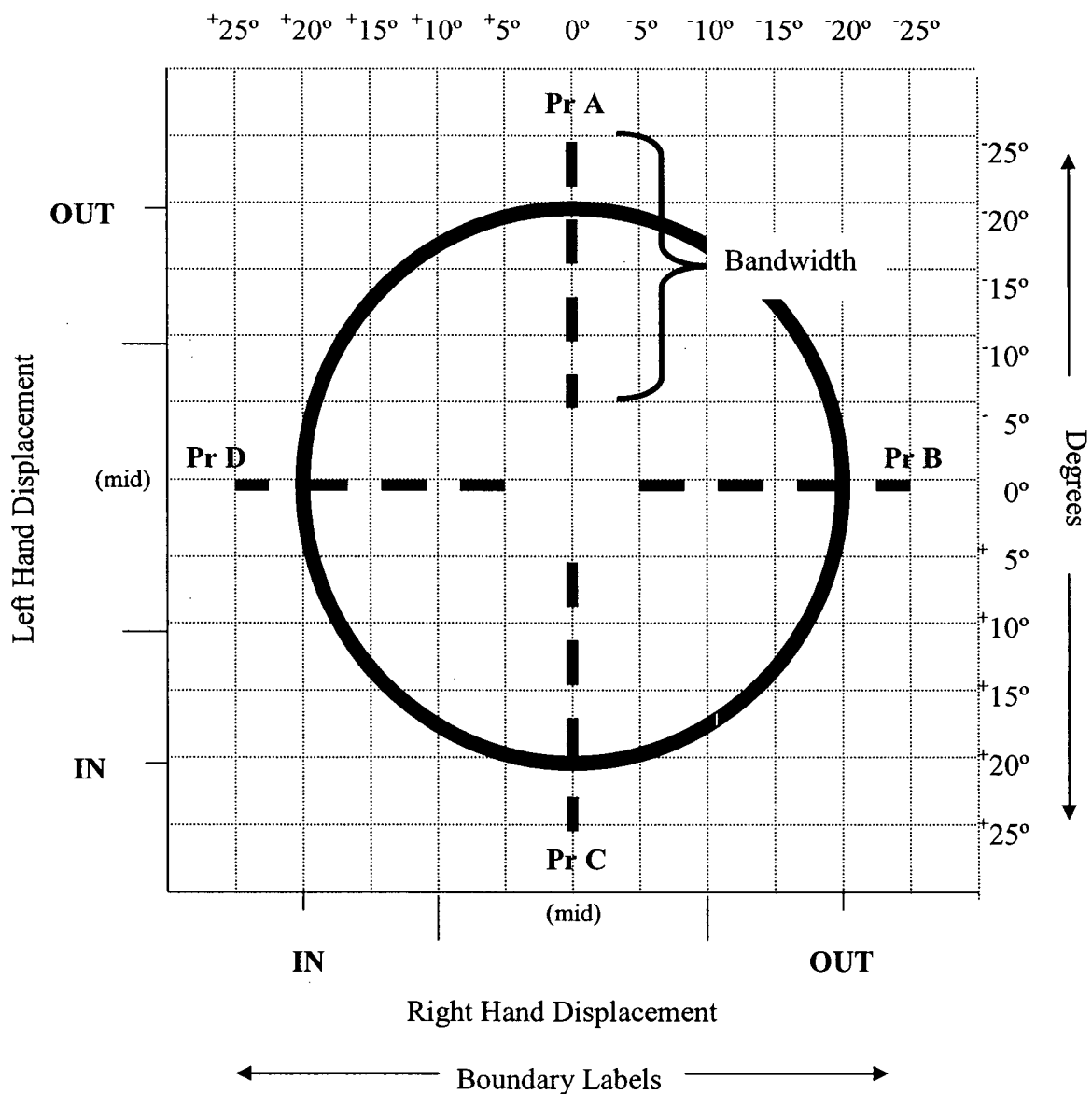
connected to a vocal response time control unit (Lafayette Instruments, 6602 A) and interfaced with the computer, picked up the individual's vocal response.

The auditory tone was delivered randomly at one of four possible positions for all trials randomly assigned as a probe condition. Probe positions were referred to as: Probe A (Pr A), Probe B (Pr B), Probe C (Pr C), and Probe D (Pr D), and were defined according to the degree of horizontal displacement of the right and left limbs (see Figure 1.2). For example, Probe A was delivered when a participant displayed 0° displacement with the right limb (i.e., the limb was mid-way between the IN and OUT boundary markers) and the left limb was within a bandwidth of $\pm 5^\circ$ and $\pm 25^\circ$ around the OUT marker. Conversely, Probe B was delivered when a participant displayed 0° displacement with the left limb and the right limb was within a bandwidth of $\pm 5^\circ$ to $\pm 25^\circ$ around the OUT marker.

In contrast to in-phase and anti-phase patterns of coordination, performing a 90° out-of-phase pattern implies that reversals in direction are not made simultaneously with both limbs. Therefore, these four conditions were designed to probe attention requirements at critical reversal points within the movement cycle as each probe type corresponded to a point of extreme flexion (-20°) or extension ($+20^\circ$) of one of the two limbs. Critical reversal points were examined because peak position may demand greater attention when compared to spatiotemporal limb position during the rest of the movement cycle. Bandwidths were designed to maintain the integrity of the probe conditions while compensating for the expected difficulties in producing the pattern at early phases of learning.

The auditory tone was delivered at variable times across probe trials. On a probe trial, the computer 'armed' itself at a randomly designated time (i.e., there was now the potential for the delivery of the auditory tone). Once armed, the respective probe 'triggered' (or sounded) when the appropriate limbs displayed 0° displacement and were within the bandwidth described above. If the limbs did not meet the criteria, an auditory tone was not delivered on that trial.

Figure 1.2. Probe positions of auditory tone displayed via a Lissajous Figure. On approximately one-third of trials, an auditory stimulus was presented at one of four possible probe (Pr) positions (identified as Pr A, Pr B, Pr C, and Pr D). When one limb is at the mid-point between the IN and OUT boundary markers (0° displacement), the other limb is within a bandwidth of $+5^\circ$ to $+25^\circ$ around the IN marker or within a bandwidth of -5° to -25° around the OUT marker, dependent on the respective probe.



Procedure

Acquisition

After participants were given an opportunity to familiarize themselves with the apparatus, the criterion circle was displayed on the monitor. Participants were informed that they could achieve this circular pattern by continuously flexing and extending the arms in a particular relationship between the two amplitude markers. Participants were instructed that they could move at their own pace¹, but the goal of the task was to produce continuous full movement cycles within each acquisition trial that matched as closely as possible to the criterion circle. The criterion for one movement cycle was explained to consist of the full moving distance between the "IN" and "OUT" markers so that each hand returned to the same starting position. Participants were told that they could move their limbs with either a right- or left-lead (i.e., the screen cursor moves in a counter-clockwise or clockwise direction, respectively), but after the first ten trials on Day 1 they were required to move the limbs in the same lead-lag relationship for the duration of the experiment. Participants were also instructed that they needed to learn the required task so that they could eventually perform 90° RP from memory. No instructions were provided to participants concerning how to produce the required circle pattern.

All trials were 13 s in duration. A 1000 Hz auditory tone signalled the start and end of each trial. The duration of each of these tones was 100 ms and 300 ms, respectively. For the first 10 s, concurrent visual feedback was provided in the form of a Lissajous figure. Relative motion feedback stayed on the screen throughout the 10 s such that a history plot emerged as the trial progressed and remained there until the completion of the trial. The latency of the real-time display was limited only by the screen refresh rate (60 Hz). Ten seconds into the trial, on-line feedback disappeared from the screen, and did not reappear until the start of the next trial. At the completion of each trial, participants received terminal relative motion feedback regarding the just-performed no-vision segment of the trial in the form of a Lissajous trace overlaying the criterion (circle) pattern and the orthogonal plot produced during the first 10 s of the trial. Participants received no experimenter-delivered augmented feedback at any time.

For the first ten trials of each session, participants performed only the circle pattern. Following these trials, participants received auditory probes on approximately one-third of the remaining trials. If the stimulus for the secondary task occurred during a trial, participants were instructed to respond by saying the word “pop” as quickly as possible. The word “pop” was chosen because the voiced consonant at the beginning of the response helps trigger the microphone. Participants were informed that there was the potential of a probe to occur in the vision or no-vision segment of the trial, but only 1 probe could occur per trial. Instructions to participants also stressed that in dual-task conditions primary task performance was of greater importance than RT to the probe and should be afforded greater priority of attention. Secondary probes occurred at each of the four probe positions 9 times, 7 of which occurred during the vision segment of the trial, while the remaining 2 occurred during the no-vision segment. Probes were presented in a randomised fashion for each participant across acquisition sessions.

Prior to, and on the final day of testing, each participant performed ten control trials during which reaction times (RT) to the auditory tone were collected in the absence of the primary task and served as a baseline measure of RT. Baseline RT was collected for later comparison to the probe-RT measures collected during the experimental trials².

Individuals participated in ten sessions of acquisition across a two-week period. For each of the ten practice sessions, participants performed a total of 100 acquisition trials, subdivided into 10 blocks of 10 trials. Each participant determined the interval between blocks, in order to offset any potential effects of fatigue across the 100 trials.

Immediate No-Feedback Transfer Tests³

At the end of each practice session (with the exception of sessions 3, 6, and 9), participants were asked to reproduce the 90° RP pattern of coordination without the use of continuous on-line visual feedback. To provide participants the opportunity to appropriately position the cursor on the computer screen, vision was briefly provided at the start of the trial (1.5 s), whereupon it was immediately

removed. Participants performed 24 no-feedback trials. Secondary probes occurred two times at each of the four probe positions (i.e., on one-third of the total trials administered). Probes were presented in a randomised fashion for each participant across no-feedback tests. Neither terminal nor experimenter-delivered augmented feedback was presented to the participant at any time.

Delayed Retention and No-Feedback Transfer Tests

The 24 no-feedback trials were repeated following a one-week retention interval of no practice. Following transfer trials, participants performed an additional 24 trials of the 90° out-of-phase task, but were given the same schedule of relative motion feedback as they had previously received while learning the 90° RP pattern.

Data Analyses

Primary Task Performance: 90° Relative Phase (RP)

To measure bimanual coordination performance, measures of relative phase (RP) were calculated. Relative phase is commonly used because it is a quantifiable evaluation of how coordination performance changes during practice. By calculating the spatiotemporal difference between the limbs at any point in time, a kinematic measure was obtained indicating the participant's success in achieving the goal pattern of 90° RP (Tsutsui, Lee, & Hodges, 1998).

In the present investigation, participants were required to continuously move their limbs 90° out-of-phase to make circular patterns. Therefore, continuous measures of RP were calculated from the angular displacement data using methods described by Scholz and Kelso (1989)⁴. Specifically, displacement data were filtered at 10 Hz for each limb and plotted as cosine functions. Peak displacements within a cycle were designated 0°, 180°, and 360° values and the intermediate points of 90° and 270° were determined at points of maximum slope displacement as a function of time (i.e., peak velocity). These points were normalized for displacement and velocity within the range of 1 to -1. The angle formed when velocity and displacement were plotted on a phase diagram gave a phase angle for each sample point (i.e., 1,000 samples/second). This was calculated for both arms and the

difference between the limbs at any point in time gave a phase angle difference from -360° to $+360^{\circ}$. Since participants could move their limbs with a right- or left-lead, RP values were normalized for comparison. That is, RP values obtained using a left-lead were wrapped to a range between 0° and 180° . From the relative phase values, the standard deviation around the mean relative phase (SD of RP) was computed to obtain an estimate of the variability in relative phase. Standard deviation of relative phase is a valuable measure for assessing acquisition of the to-be-learned pattern since it is an index of pattern stability. Variability serves to illustrate the exploration of new coordination patterns and the break from preferred coordination tendencies at the start of practice, as well as determine the stability and quality of the newly acquired pattern of coordination at the end of practice.

Root mean square error (RMSE) relative to the 90° RP pattern of coordination was calculated as an overall measure of performance error. Specifically, RMSE was obtained from the square root of the sum of constant error squared and total number of observations. This measure has been commonly used by others (e.g., Hodges & Franks, 2000; Tsutsui et al., 1998) because of its sensitivity to both bias and variability. This is important when considering the problems inherent in averaging relative phase values. Early in learning, for example, a participant may switch between 0° and 180° RP resulting in a mean RP value of 90° . Performance would then be incorrectly assessed as accurate with respect to the criterion pattern. However, as a result of the switch between patterns, within-trial variability would be high. This variance is taken into account when using RMSE and the error score is modified accordingly. Although RMSE is made up of both within-trial accuracy and within-trial standard deviation, SD of RP was also analyzed separately (as previously stated). High values of RMSE may be due to one of, or both, variability and accuracy. Therefore, variability is an important variable to examine on its own accord (Hodges, 2001).

In addition to RMSE and SD of RP, the frequency of each cycle was quantified. Cycle time was defined as the time interval from peak flexion to peak flexion, while cycle frequency was defined as the inverse of cycle time (Frequency (in Hz) = $1 / \text{cycle time (in seconds)}$). For every trial, cycle frequency was averaged

across each segment to provide the self-selected movement frequency of the criterion relative phase pattern.

Secondary Task: Probe-RT

Probe-RT (in ms) was measured as the interval between the onset of the auditory stimulus and the moment at which the microphone detected the participants' vocal response. To determine baseline RT, a mean reaction time was determined for pre- and post- acquisition control conditions and submitted to a one-way repeated measures analysis of variance. No significant difference was found between pre-acquisition ($M = 392$ ms, $SD = 56$ ms) and post-acquisition ($M = 411$ ms, $SD = 59$ ms) baseline RT ($p = .357$). Therefore, mean RT for the secondary task control condition was calculated using both pre- and post-acquisition measures⁵ ($M = 402$ ms, $SD = 58$ ms).

Results and Discussion

The results are presented according to three main questions, namely: (a) Did performance improve with practice? (b) Did performance deteriorate with the withdrawal of concurrent visual feedback? and (c) Did extended practice on a bimanual coordination task reduce and eventually eliminate dual-task interference?

Question 1: Did Performance of the Required Pattern Improve with Practice?

Changes in Pattern Accuracy and Stability across Acquisition. Initial analysis of the data examined the effect of practice on the acquisition of a cyclical bimanual coordination task requiring a phase offset of 90°. The 100 trials performed in each acquisition session were divided into 5 blocks of 20 trials. Dependent measures (i.e., RMSE; SD of RP) were submitted to a Day (9) x Segment (vision, no-vision) x Block (5) ANOVA, with repeated measures on all factors. In the current section, results will only be presented for day and block. Presentation and discussion of 90° RP performance with respect to segment will be examined in Question 2, which focuses on the effects of removing concurrent visual feedback on performance of the

criterion pattern. As such, individual participant data in this section will only focus on the vision segment of the trial. In terms of the analysis, participants displayed considerable problems in producing the required 90° RP pattern on Day 1. Besides the difficulties inherent in the acquisition of any complex bimanual coordination task, the self-regulatory nature of the experimental procedure was a contributing factor to the difficulties observed (i.e., no explicit instructions were given to participants regarding how to produce the 90° criterion pattern and participants were instructed to move at their own pace). Although participants were instructed to make full movement cycles, some individuals moved so slowly they did not complete one full movement cycle within a trial (see Figure 1.7). Due to the lack of data in the initial block of practice for these participants, Day 1 could not be included in the statistical analysis of the acquisition sessions. However, Day 1 data are presented in Figures 1.5 - 1.8 for discussion of participants' individual data. All post-hoc comparisons were performed using the Tukey HSD procedure. The level adopted for achievement of statistical significance was $p \leq .05$.

An overall picture of the evolution of task performance is illustrated in Figure 1.3 across all participants. Root-mean-square error (RMSE) is presented in the top panel, while standard deviation of relative phase (SD of RP) is presented in the bottom panel. These data illustrate several features characteristic for learning a new bimanual coordination pattern (see Zanone & Kelso, 1997). As practice proceeded, there was an improvement in performance as reflected by a change in both pattern accuracy (RMSE) and stability (SD of RP). Practice substantially improved performance towards the criterion pattern (i.e., 90° RP), and variability of the pattern decreased. Most importantly, this improvement continued throughout the nine days of acquisition for both measures. This is confirmed by a main effect across days for RMSE, $F(8, 40) = 4.87$, $p = .0003$, and SD of RP, $F(8, 40) = 5.68$, $p = .0001$. Percent improvement scores are illustrated in Figure 1.4 for RMSE (upper panel) and SD of RP (bottom panel). When compared to Day 2, RMSE improved by 8% for Days 3 and 4, respectively⁶. This improvement continued through Day 5 (14%) and Day 6 (19%), followed by a plateau. In the final days of acquisition, pattern accuracy improved by 24% and 25% (Days 9 and 10, respectively) in comparison to Day 2

Figure 1.3. RMSE of goal relative phase (top panel) and SD of RP (bottom panel) across 9 days of acquisition (Error bars = SEM).

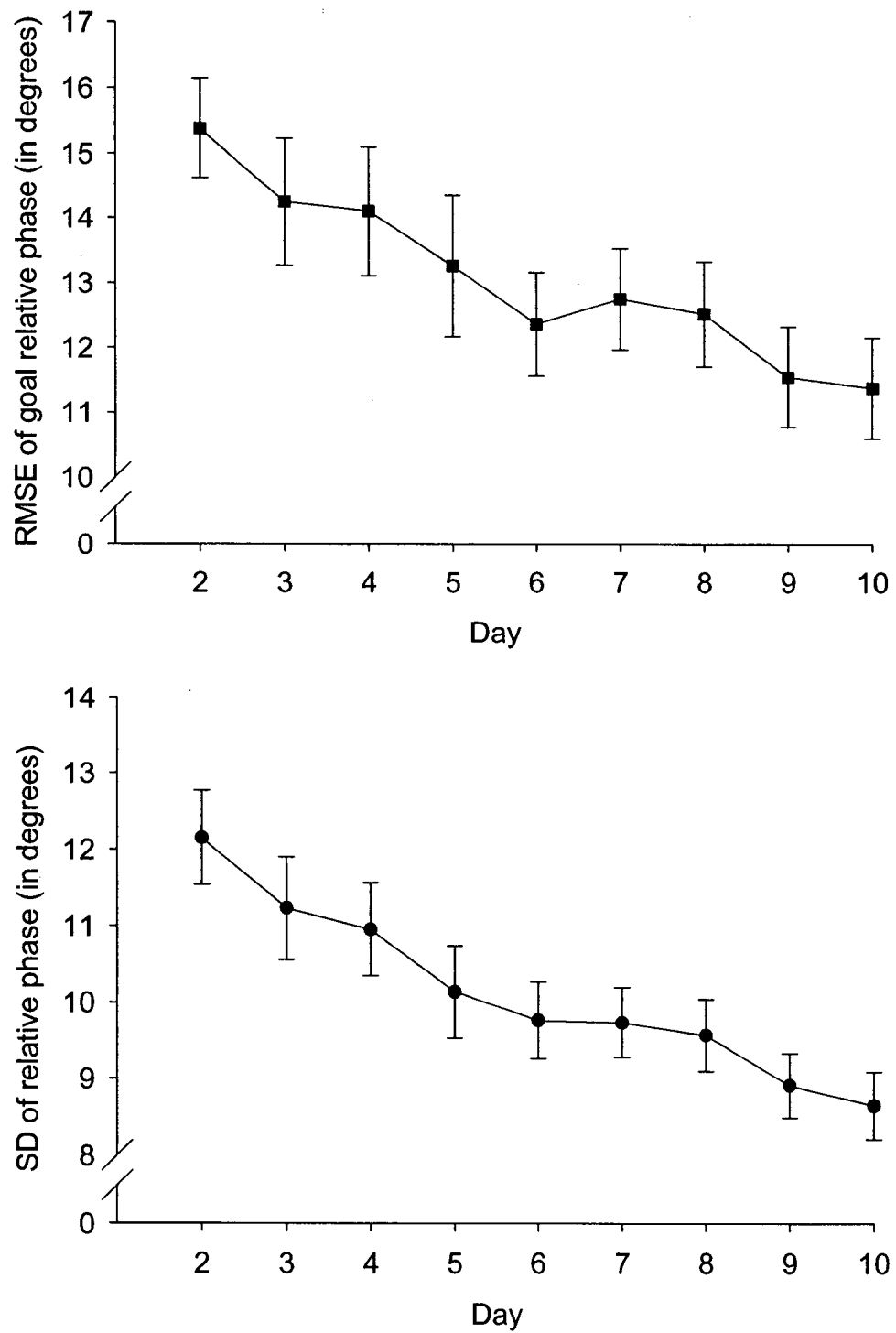
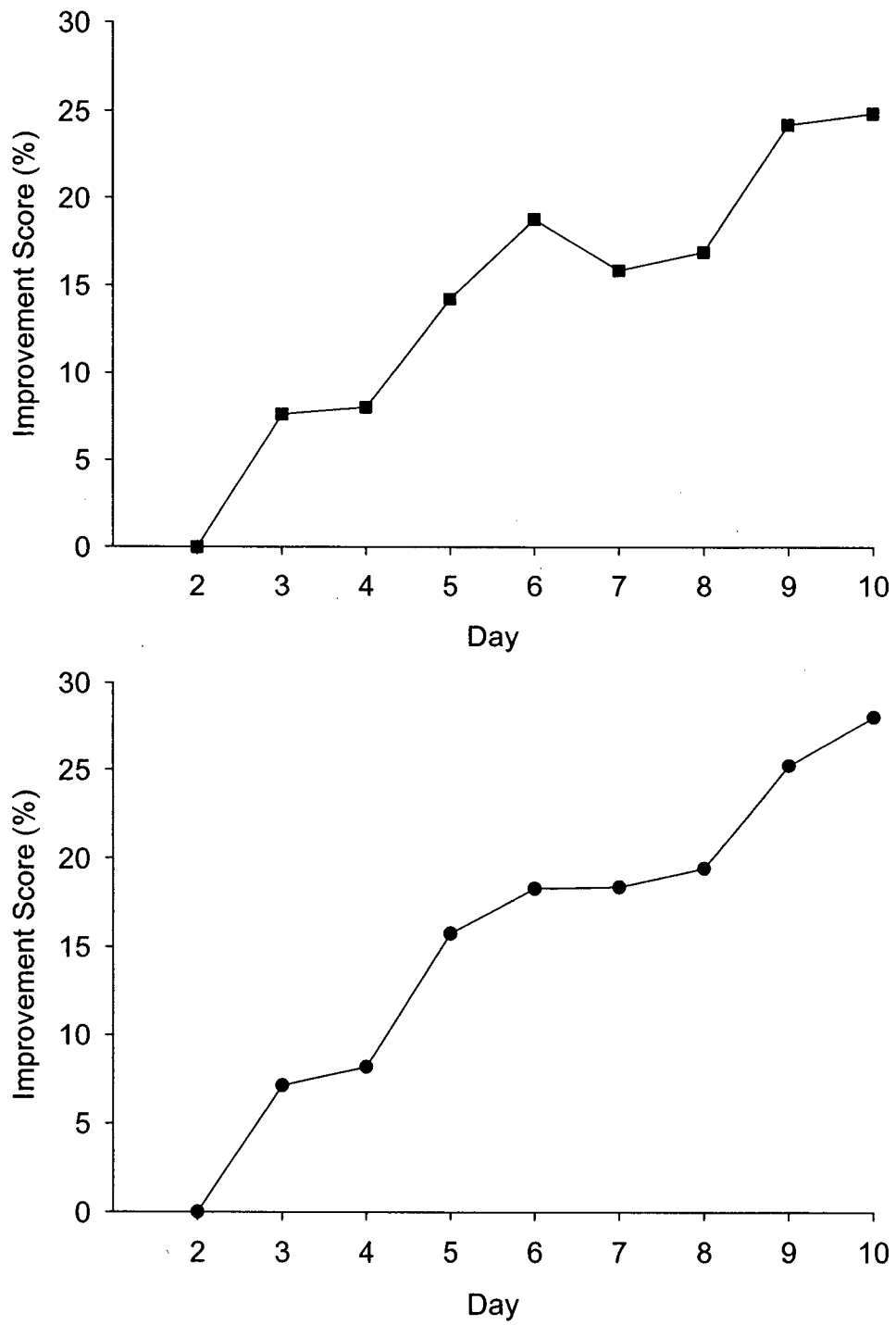


Figure 1.4. Percent Improvement from Day 2 for RMSE of goal relative phase (top panel) and SD of RP (bottom panel).



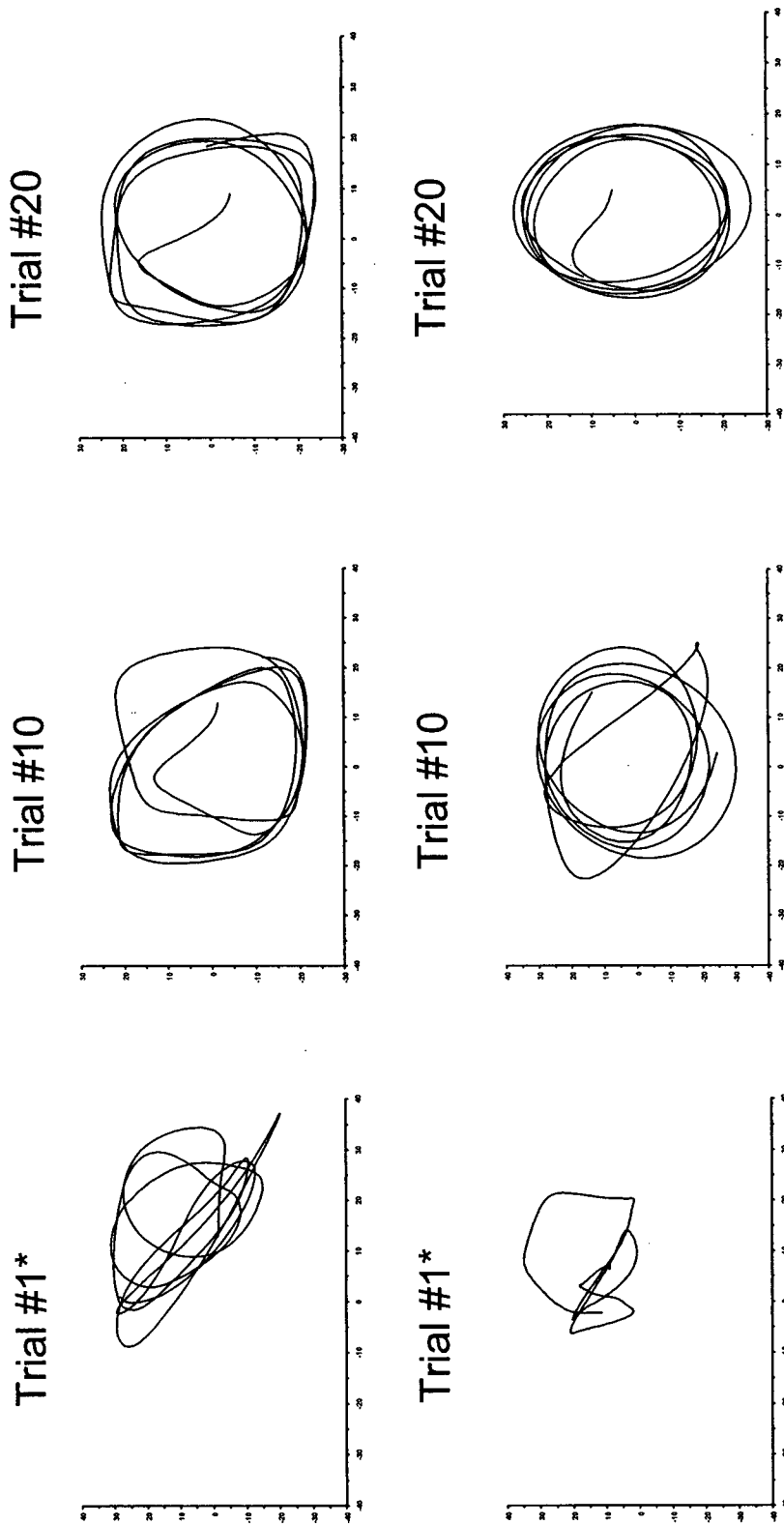
performance. Similar percent changes were evidenced for SD of RP. By Days 4 and 8, pattern stability improved by 8% and 19%, respectively, and reached a maximal level of improvement on Day 10 (28%).

Performance of the 90° out-of-phase task showed a general increase in accuracy across blocks for RMSE, although this was not significant ($p = .089$). In comparison, a significant block effect was observed for SD of RP, $F(4, 20) = 4.78$, $p = .007$. Analysis revealed that performance of the 90° RP task was significantly more stable in Blocks 3 ($M = 10.0^\circ$, $SD = 4.6^\circ$) and 5 ($M = 9.8^\circ$, $SD = 4.0^\circ$) when compared to Block 1 ($M = 10.6^\circ$, $SD = 4.1^\circ$).

Changes in Cycle Frequency across Acquisition. Participants performed the 90° RP pattern of coordination at a self-selected frequency. To gauge preferred rates of movement for the criterion task after Day 1, cycle frequency was averaged across each segment for every trial. The 100 trials of each acquisition session were then divided into 5 blocks of 20 trials and submitted to a Day (9) x Segment (vision, no-vision) x Block (5) ANOVA, with repeated measures on all factors. Findings revealed no significant main effect for day ($p = .708$) or block ($p = .734$). From Day 2 to the end of acquisition, mean preferred rate of cycle frequency was 0.6 Hz (range = 0.4 Hz to 0.9 Hz). Stated differently, participants performed approximately 8 cycles per trial on average. This was maintained across blocks. Only one participant increased cycle frequency from 0.4 Hz to 0.6 Hz with practice (see Question 2, Table 1.1).

Individual Performance Data. Individual performances on the 90° out-of-phase task are illustrated in Figures 1.5 to 1.8 for the vision segment of acquisition. In each of these figures, the data has been presented in the form of Lissajous figures. Some interesting insights into the acquisition process can be obtained through visual inspection of these figures. Attainment of a circular configuration occurred rather quickly for two participants (see Figure 1.5). On the very first practice trial, it is evident that Participant 2 (top panel) is attempting to break free of an initial bias to anti-phase. On trial 10, the first full movement cycle is circular in

Figure 1.5. Performance during the vision segment for Participants 2 (top panel) and 5 (bottom panel) on selected acquisition trials, Day 1 (x-axis = right forearm displacement; y-axis = left forearm displacement).



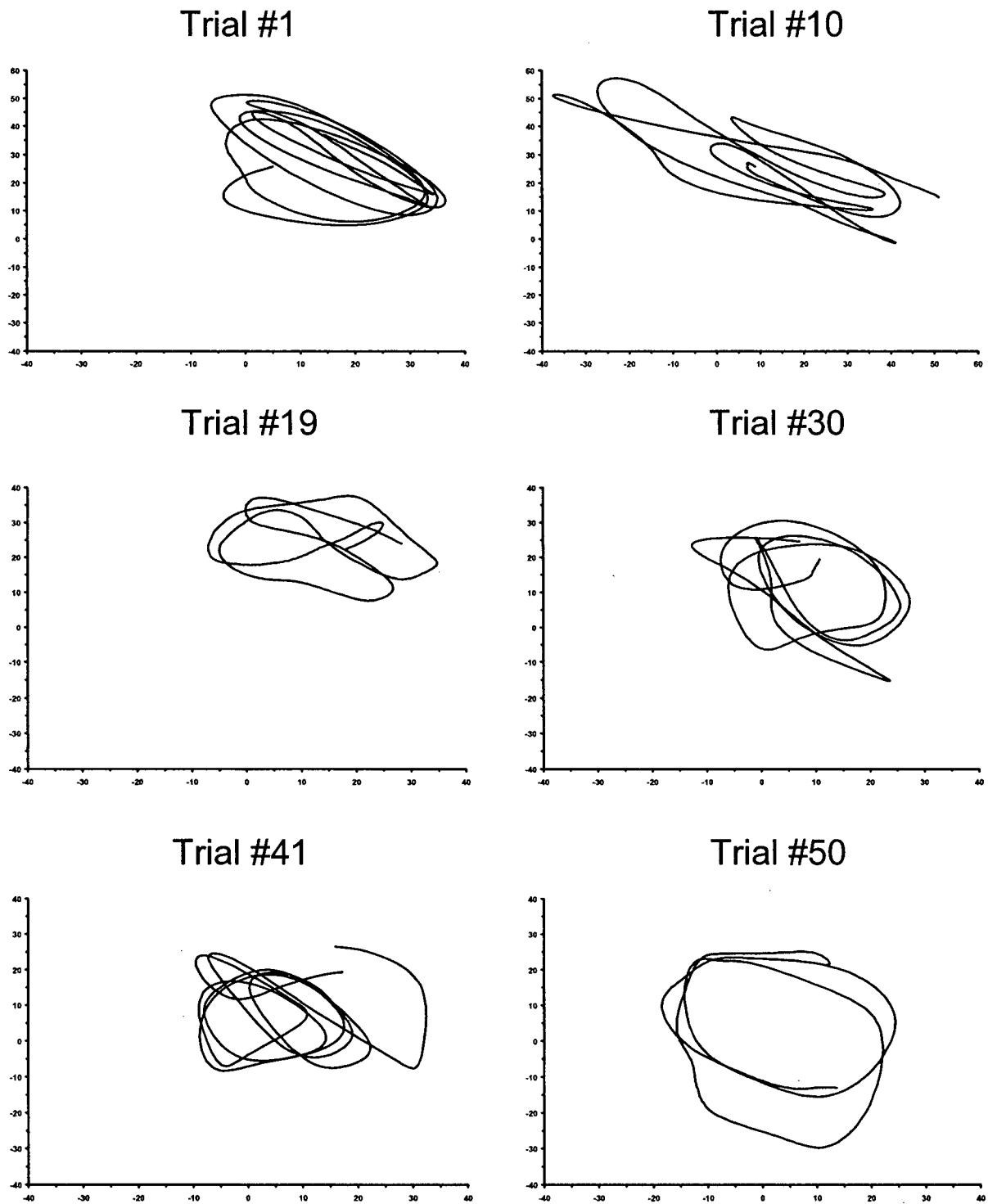
*Note: A scale of $\pm 40^\circ$ for the x-axis and $\pm 30^\circ$ for the y-axis is representative of what participants would have viewed on the computer monitor. On Trial #1 both participants made large movements in terms of amplitude, which resulted in a relative motion plot that went off the screen. Therefore, for illustrative purposes only, the scale for the y-axis is presented as $\pm 40^\circ$ in the above figure for Trial #1. The same scaling will appear in any other figures where the same situation applies.

nature, but then the produced pattern drifts to a more elliptical form for the remainder of movement cycles. By the end of the first block of 20 practice trials, emergence of the circle pattern became more consistent. Remnants of the early influences of pre-existing coordination patterns were replaced by the criterion circle pattern whereby the occupation of elliptical configurations (or diagonals) were no longer evident when attempting to perform a phase offset of 90° with the limbs (see Swinnen et al., 1997). For participant 5, performance of a relatively consistent pattern near 90° relative phase occurs even more rapidly. Although small in amplitude, the participant coordinated the limbs to produce a pattern that resembled a circular configuration by the end of the first trial. By trial 10, performance of 90° RP rapidly improved, although the participant demonstrated a tendency to spontaneously shift towards anti-phase in the middle of the trial, followed by a return to a phase offset of 90° on the very next movement cycle. This is indicated by the occupation of an elliptical configuration (or diagonal) in the Lissajous trace. Maintenance of a relatively consistent 90° out-of-phase pattern was produced by the end of block 1.

For several individuals the acquisition of the criterion pattern did not occur as rapidly when compared to the evolution of task performance for Participants 2 and 5. Participant 6, for example, was unable to maintain a pattern of performance near 90° RP until the middle of Day 1 (see Figure 1.6). Early in acquisition, performance was strongly biased toward an anti-phase pattern. Slowly, the participant was able to break free of the bias. This is indicated by an increase in pattern variability as the individual searched for the required phasing over a period of 50 trials. The end of the third block of trials demonstrated emergence of a pattern larger in amplitude and circular in nature.

One factor that may have contributed to the slow rate of acquisition for several participants was that individuals were required to learn the 90° RP pattern at their own pace. Most experiments investigating the acquisition of bimanual coordination have required participants to move at a pre-determined movement frequency such as 1 Hz (e.g., Hodges & Lee, 1999). When permitted to move at a self-selected frequency, the tendency of the performer was to move very slowly. In

Figure 1.6. Performance during the vision segment for Participant 6 on selected acquisition trials, Day 1 (x-axis = right forearm displacement; y-axis = left forearm displacement).



this approach, participants often attempted to learn what each limb did by moving the limbs in an independent fashion, rather than the nature of the phasing (or new coupling) relationship between the two limbs. In contrast, it appears that requiring an individual to make, for example, one complete movement cycle per second early in learning, serves to increase the variability of the currently performed pattern. This encourages the learner to break away from pre-existing coordination tendencies and more readily explore possible solutions to the movement problem, which in turn, facilitates the rate of acquisition early in practice. Figure 1.7 demonstrates the former strategy employed by Participant 1. This individual did not coordinate the limbs to produce one complete movement cycle until the second block of trials.

Although participants displayed different rates of acquisition at early stages of the learning process, all participants were able to produce a pattern of performance near 90° relative phase by the end of practice on the first day of acquisition. In essence, participants acquired a general idea of the 90° out-of-phase pattern on Day 1, and continued to improve the accuracy and the stability of the required pattern across the entire time course of practice. This improvement was facilitated by the provision of continuous on-line feedback, which presented individuals an opportunity to use information regarding the relative motions of the limbs during the performance to correct and optimize their movements. Figure 1.8 demonstrates the evolution of 90° RP performance across extended practice for a representative participant when relative motion feedback was available to guide motor performance.

Question 2: Did Performance Deteriorate with the Withdrawal of Concurrent Visual Feedback?

Vision versus No-Vision during Acquisition. In acquisition, concurrent on-line visual feedback was removed ten seconds into the trial, and did not reappear until the start of the next trial. Performance of RMSE and SD of RP are illustrated in Figures 1.9 and 1.10 for the 8.5 s vision segment (left panel) and the 3 s no-vision segment (right panel) collapsed across all participants. Analysis of RMSE (see Question 1) revealed a significant main effect for segment, $F(1, 5) = 6.73$, $p = .049$.

Figure 1.7. Performance during the vision segment for Participant 1 on selected acquisition trials, Day 1 (x-axis = right forearm displacement; y-axis = left forearm displacement).

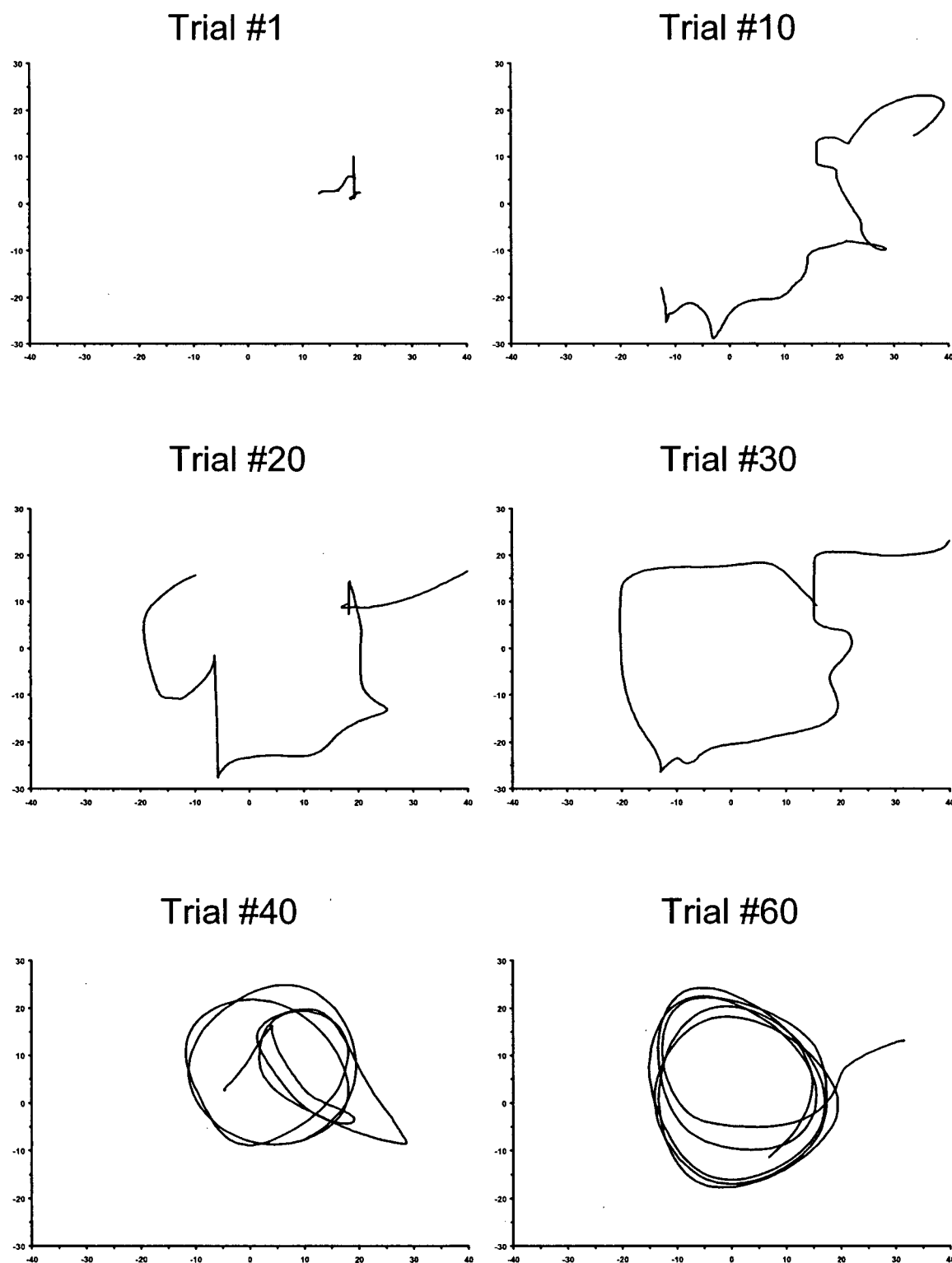
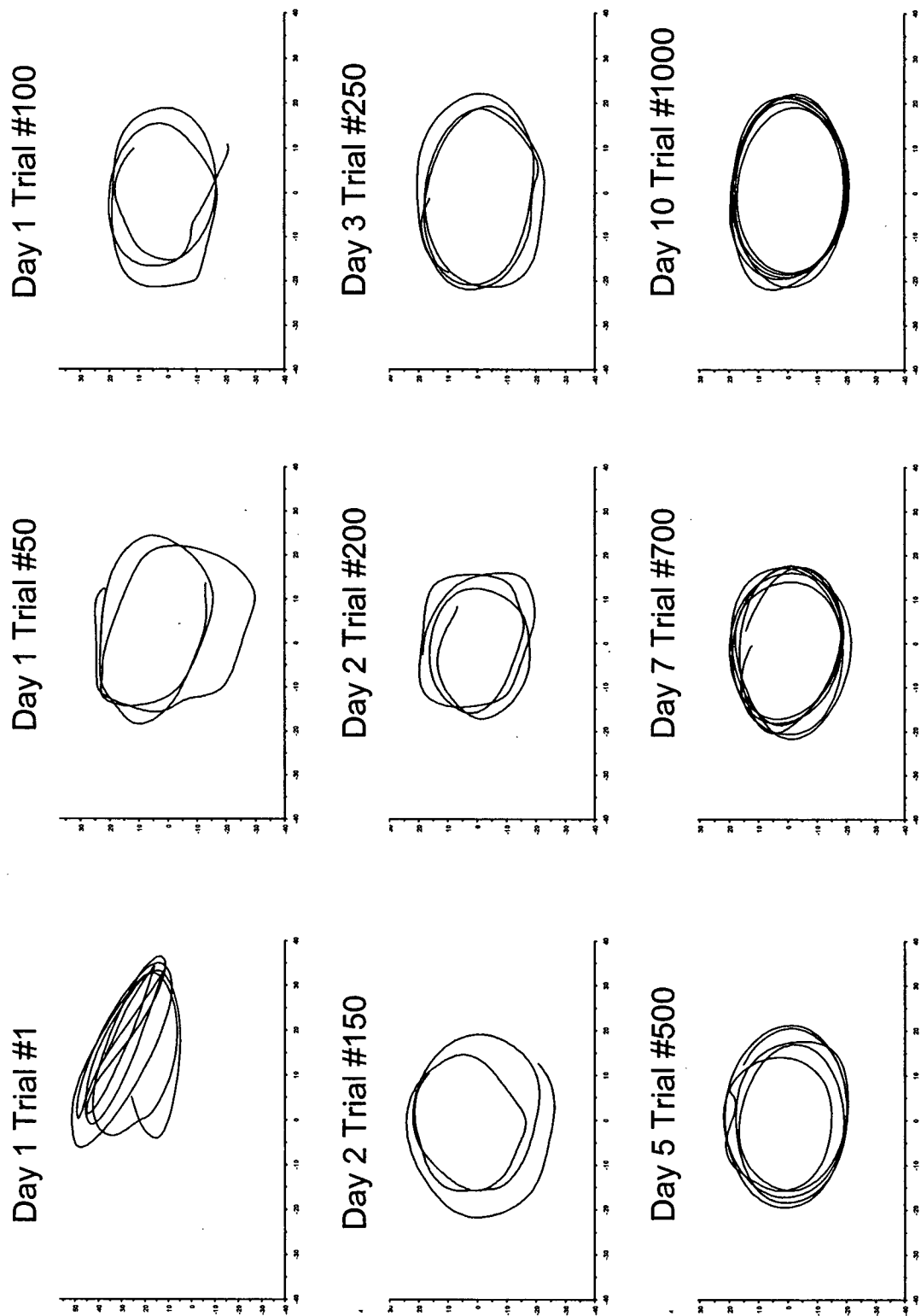


Figure 1.8. Performance during the vision segment for Participant 5 on selected acquisition trials across days (x-axis = right forearm displacement; y-axis = left forearm displacement).



A lower RMSE was observed during the vision segment of the trial as compared to the no-vision segment on each day of acquisition, as revealed by further post-hoc analysis (Figure 1.9).

Analysis of SD of RP revealed a significant interaction effect for day and segment, $F(8, 40) = 2.94$, $p = .011$. Stability of the 90° RP pattern increased at a faster rate when provided with relative motion feedback as compared to the no-vision segment, when concurrent feedback was removed. Post-hoc analysis revealed that performance of the 90° RP task was significantly more stable in the vision segment as compared to the no-vision segment from Day 4 to the final day of acquisition; although, the 90° out-of-phase task reached its greatest stability on Day 10 for both segments (Figure 1.10).

Findings also revealed a significant interaction for segment by block for both RMSE, $F(4, 20) = 7.08$, $p = .001$, and SD of RP, $F(4, 20) = 4.51$, $p = .009$. For vision, the 90° out-of-phase pattern was significantly more variable and performed with the greatest error in Block 1 when compared to all other blocks of acquisition, except Block 2. There was no significant difference between blocks for the no-vision segment of the trial.

Finally, when comparing cycle frequency between conditions of vision and no-vision, no significant main effect for segment was observed ($p = .193$). Mean cycle frequency was 0.6 Hz, which was maintained across segments from Day 2 to the end of acquisition. These findings suggest that performance differences between vision and no-vision were not a result of differences in mean cycle frequency. Table 1.1 displays mean cycle frequency during the vision and no-vision segment for each participant collapsed across blocks.

These data suggest that visual feedback has a critical impact on the acquisition and performance of a 90° out-of-phase pattern of coordination. We predicted that withdrawal of concurrent visual feedback early in practice would cause a drift from the produced pattern to a more stable intrinsic pattern of coordination. However, with practice, it was hypothesized that the performer would gain the capability to maintain performance of 90° RP, even upon the withdrawal of concurrent visual feedback for the last 3 s of the trial. This prediction is supported in

Figure 1.9. RMSE of goal relative phase for the vision (left panel) and the no-vision segment (right panel) across 9 days of acquisition (Error bars = SEM).

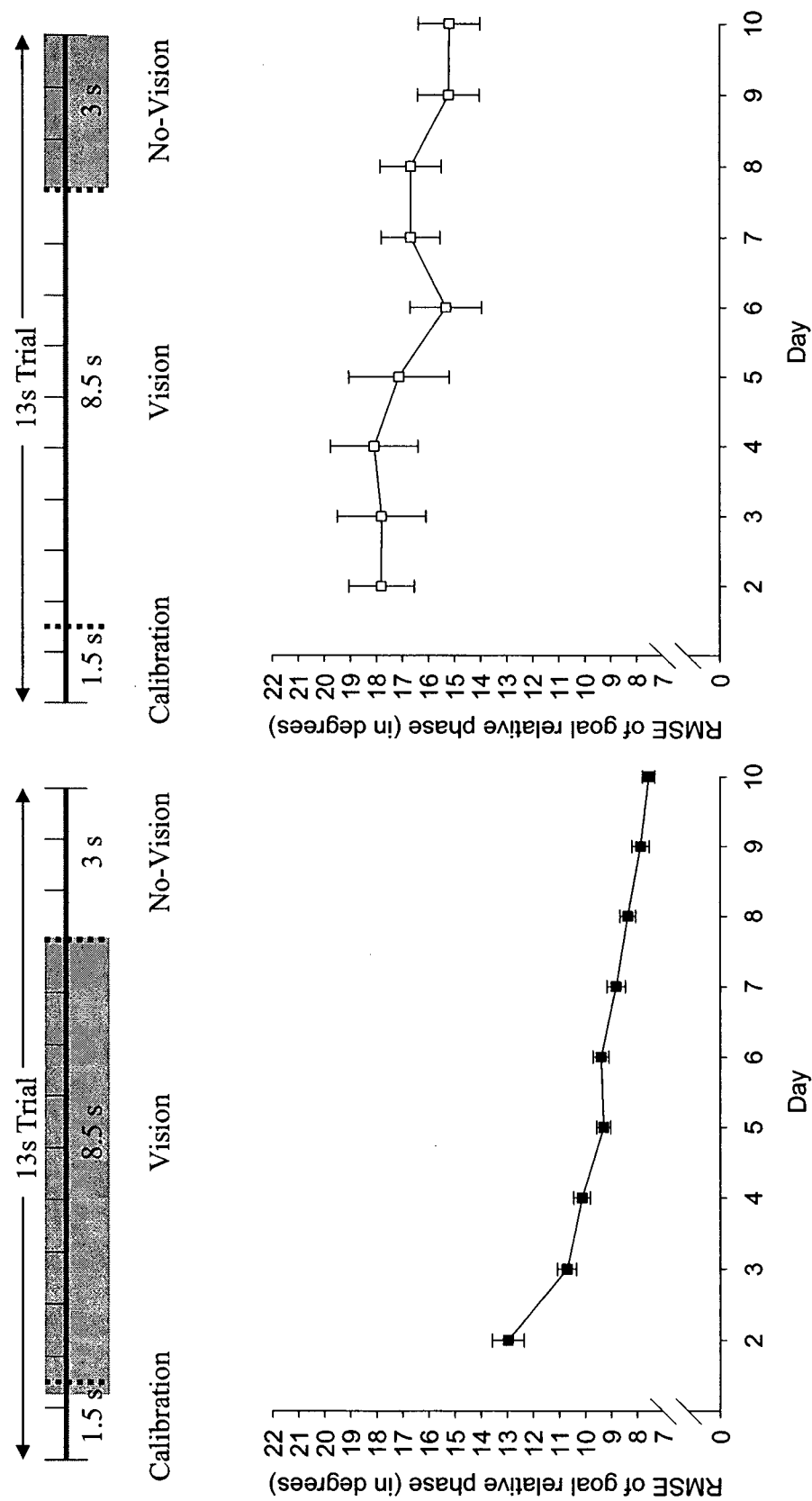


Figure 1.10. Standard deviation of relative phase for the vision (left panel) and the no-vision segment (right panel) across 9 days of acquisition (Error bars = SEM).

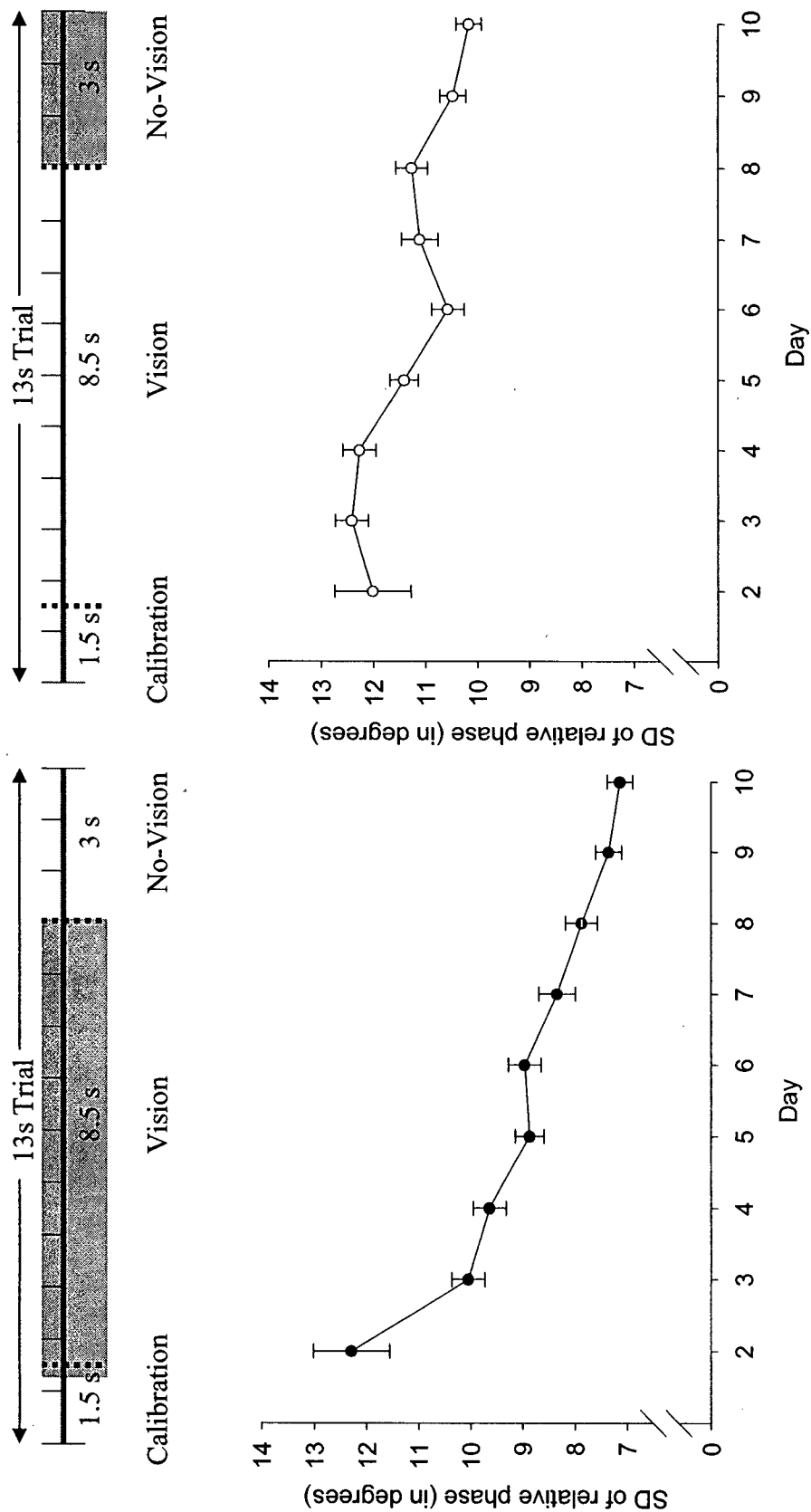


Table 1.1

Mean cycle frequency during the vision and no-vision segment for each participant collapsed across block.

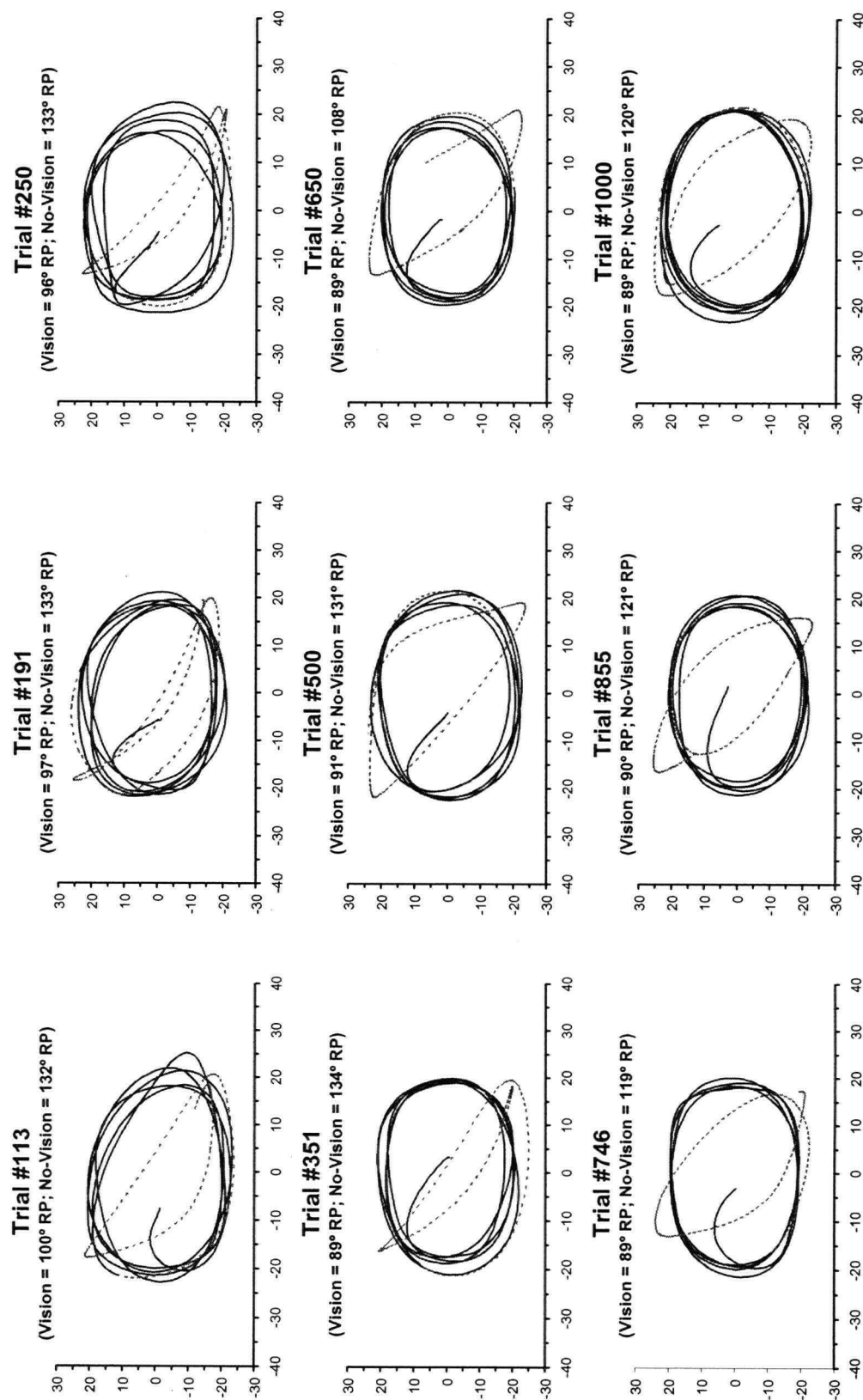
		Day									
1 ¹		2	3	4	5	6	7	8	9	10	
Participant	V NV	V NV	V NV	V NV	V NV	V NV	V NV	V NV	V NV	V NV	
1	0.4 0.3	0.5 0.5	0.6 0.6	0.6 0.6	0.7 0.7	0.6 0.6	0.6 0.6	0.5 0.5	0.6 0.6	0.6 0.6	
2	0.5 0.5	0.6 0.6	0.5 0.5	0.5 0.5	0.5 0.5	0.4 0.4	0.5 0.5	0.4 0.4	0.5 0.5	0.5 0.5	
3	0.3 0.4	0.4 0.5	0.4 0.5	0.4 0.5	0.4 0.5	0.4 0.4	0.4 0.4	0.5 0.5	0.5 0.5	0.5 0.5	
4	0.4 0.4	0.6 0.6	0.7 0.8	0.7 0.8	0.7 0.8	0.7 0.8	0.6 0.6	0.6 0.6	0.7 0.8	0.8 0.8	
5	0.7 0.7	0.8 0.8	0.8 0.8	0.9 0.9	0.8 0.8	0.8 0.8	0.8 0.8	0.8 0.8	0.8 0.8	0.7 0.7	
6	0.4 0.5	0.4 0.4	0.4 0.5	0.4 0.5	0.5 0.5	0.5 0.6	0.6 0.6	0.6 0.7	0.6 0.6	0.6 0.6	

¹ Day 1 performance was not included in the statistical analysis because several participants were unable to perform one complete movement cycle in a 13 s trial during the first block of the acquisition session.

only two of the six participants. The rest of the participants routinely demonstrated a phase drift upon withdrawal of concurrent visual feedback even on the final day of the extended acquisition period. When examining anecdotal evidence, these participants disclosed that they were taken aback to see the extent to which they had drifted from the criterion pattern when viewing terminal feedback of the just-performed no-vision trial segment. The participants commented that their performance during the no-vision segment surprised them, especially as practice continued across days and when taking into consideration their efforts to maintain the required pattern for the last 3 s of the trial. For these participants, differences between vision and no-vision performance remained prominent until the end of acquisition. Figure 1.11 illustrates the drift effect across acquisition for Participant 2 in the form of Lissajous figures. During the vision segment, the participant produced a pattern resembling the criterion early in the learning process. This pattern was produced with considerable accuracy and consistency by Day 4, which persisted for the duration of acquisition. However, when visual feedback was withdrawn 10 s into the trial, the produced pattern typically shifted away from the criterion towards a more stable anti-phase bias. This phenomenon continued even after 1,000 trials of practice. Rather than demonstrate a capability to maintain a phase offset of 90° , Participant 2 produced an elliptical configuration, which actually became more stable and accurate across practice trials.

Within the motor learning literature, one issue that has arisen concerns the frequency with which feedback is presented to the individual in the learning environment. Although the regular provision of augmented information has been shown to facilitate performance during acquisition, research has also revealed that performance deteriorates in transfer conditions when feedback is no longer available to guide and correct the required movement (e.g., Salmoni, Schmidt, & Walter, 1984). In the present experiment, most participants performed substantially better in the vision segment as compared to the no-vision segment. Although participants received both conditions within each trial, participants' were exposed to relative motion feedback for a greater portion of time (total vision = 10 s; total no-vision = 3 s). Therefore, it is possible that participants exhibiting a performance decrement in the

Figure 1.11. Individual trial data across acquisition displayed as Lissajous figures for Participant 2. The solid line represents the vision segment, and the dotted line represents the no-vision segment (x-axis = right forearm displacement; y-axis = left forearm displacement).



no-vision segment developed a dependency on the feedback information, which they used on-line to monitor performance. As a consequence, these participants had difficulty maintaining performance of the 90° out-of-phase task when visual feedback was removed and performance drifted away from the criterion pattern to more intrinsically stable modes of coordination. This observation also supports the recent proposals of Proteau and colleagues (e.g., Tremblay & Proteau, 1998) who suggest that there is an optimal source of afferent information for successful performance of a task. Early in learning, it is possible that these participants deemed relative motion feedback as the most efficient information source available and processed it to the detriment of other information sources such as proprioception. In contrast, participants who were able to maintain performance under no-vision conditions may have used the relative motion feedback to update and refine the processing of more intrinsic sources of afferent information, rather than place a reliance on vision to guide the on-going movement (see Swinnen et al., 1997). As such, they were capable of maintaining performance in the absence of the relative motion feedback.

Pattern Accuracy and Stability under Conditions of Transfer. Participants were also asked to reproduce the 90° out-of-phase task without use of on-line visual feedback in immediate and delayed no-feedback transfer tests. On days when transfer tests were conducted comparisons were made between the transfer tests (i.e., immediate transfer = Days 1, 2, 4, 5, 7, 8, 10; delayed transfer = Day 11) and the last 24 trials of acquisition. The 24 trials performed in each no-feedback transfer test (immediate and delayed) were divided into 4 blocks of 6 trials. The last 24 trials of acquisition on each no-feedback test days were also divided into 4 blocks of 6 trials. For each dependent measure, final blocks of acquisition were then compared to transfer blocks in a Day (1, 2, 4, 5, 7, 8, 10, 11) x Condition (acquisition, transfer) x Segment (8.5 s, 3 s) x Block (4) ANOVA, with repeated measures on all factors.

Analysis of variance revealed a significant three-way interaction between day, segment, and condition for RMSE, $F(7, 35) = 2.30$, $p = .048$. Although performance improved with practice for both conditions, changes in performance were greater for the no-feedback transfer condition when compared to acquisition

(top panel, Figure 1.12). Post-hoc analysis revealed that the acquisition performance was superior to performance under the transfer condition for all days, except Day 10 (Day 10: \bar{M} acquisition = 11.4° , $SD = 5.3^\circ$; \bar{M} transfer = 21.6° , $SD = 9.3^\circ$). This level of pattern accuracy was retained after a one-week retention interval of no practice (Day 11: \bar{M} acquisition = 13.0° , $SD = 6.8^\circ$; \bar{M} transfer = 20.7° , $SD = 4.9^\circ$). When relative motion feedback was provided during the 8.5 s segment of acquisition, participants performed the 90° out-of-phase pattern with greater accuracy when compared to performance during the 8.5 s segment of no-feedback in the transfer condition. However, when visual feedback was withdrawn in acquisition, performance deteriorated and no significant difference was displayed between the final 3 s of acquisition and transfer performance.

Analysis of SD of RP revealed that stability of the 90° RP pattern increased in both conditions (bottom panel, Figure 1.12) as evidenced by a main effect for Day, $F(7,35) = 6.04$, $p = .0001$. Post-hoc analysis indicated that the SD of RP on Day 1 was significantly different than variability of the pattern observed on Days 4 through 11. There was also a main effect for condition, $F(1, 5) = 16.89$, $p = .009$. Similar to RMSE, these data illustrate that acquisition performance was superior when compared to performance under the transfer condition. Pattern stability was greatest when participants were provided with concurrent visual feedback during acquisition, but variability increased when vision was removed. Similar levels of variability were demonstrated for the final 3 s of acquisition performance and performance under no-feedback transfer conditions.

Although all participants showed decreases in performance under no-feedback transfer conditions, there was a range in the severity and duration of this decrement. Acquisition and transfer performance on the 90° out-of-phase task are compared in Figures 1.13 and 1.14 for two participants in the form of Lissajous figures. Figure 1.13 represents the performance of a participant who demonstrated highly accurate and consistent performance on 90° RP at early stages of the learning process. This individual was also able to maintain the required phase offset when relative motion feedback was removed during the no-vision segment of the acquisition trials (left panel). When the individual was tested at early stages of

Figure 1.12. RMSE of goal relative phase (top panel) and SD of RP (bottom panel) for condition (acquisition, transfer) across days (Error bars = SEM).

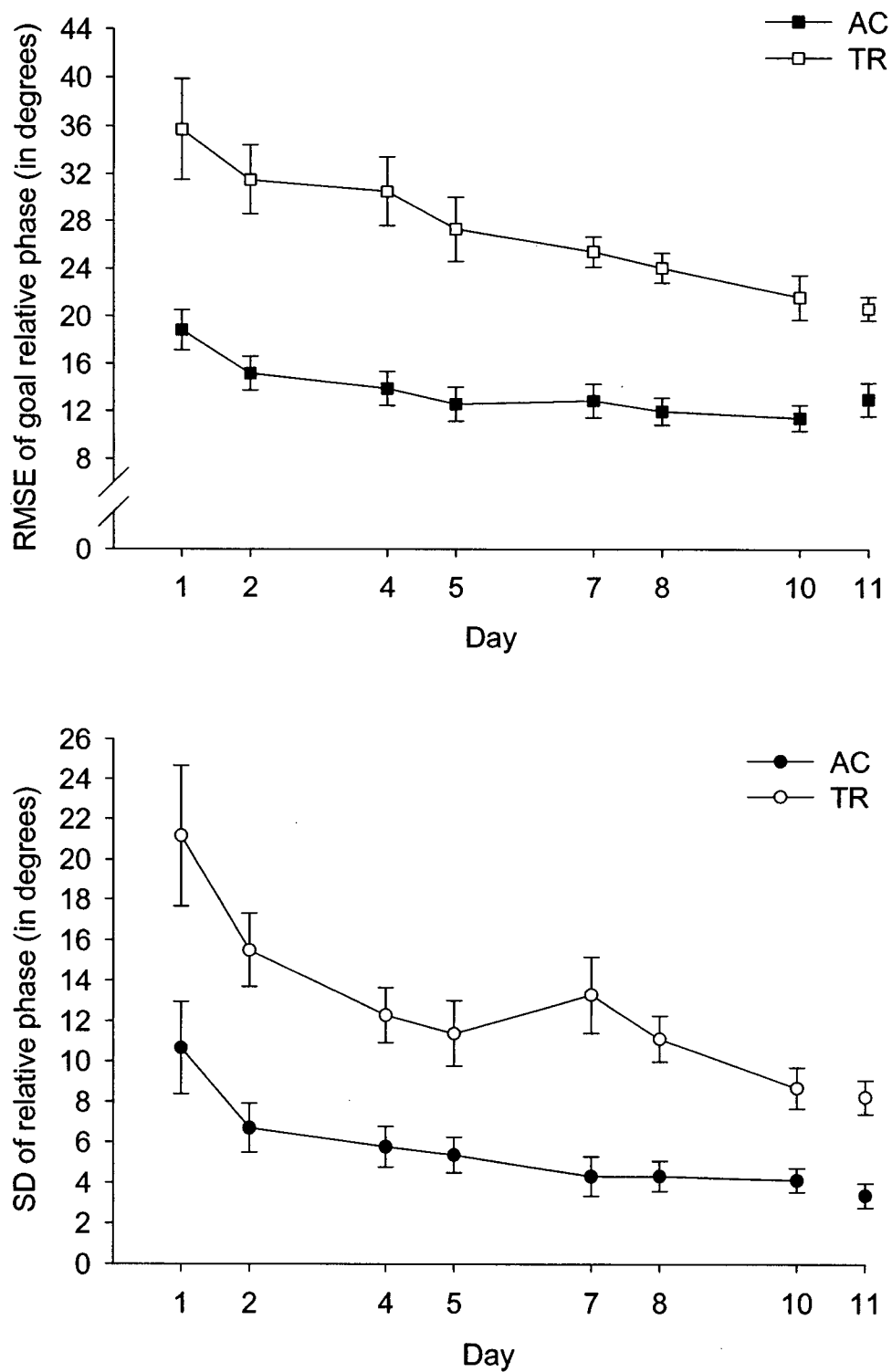
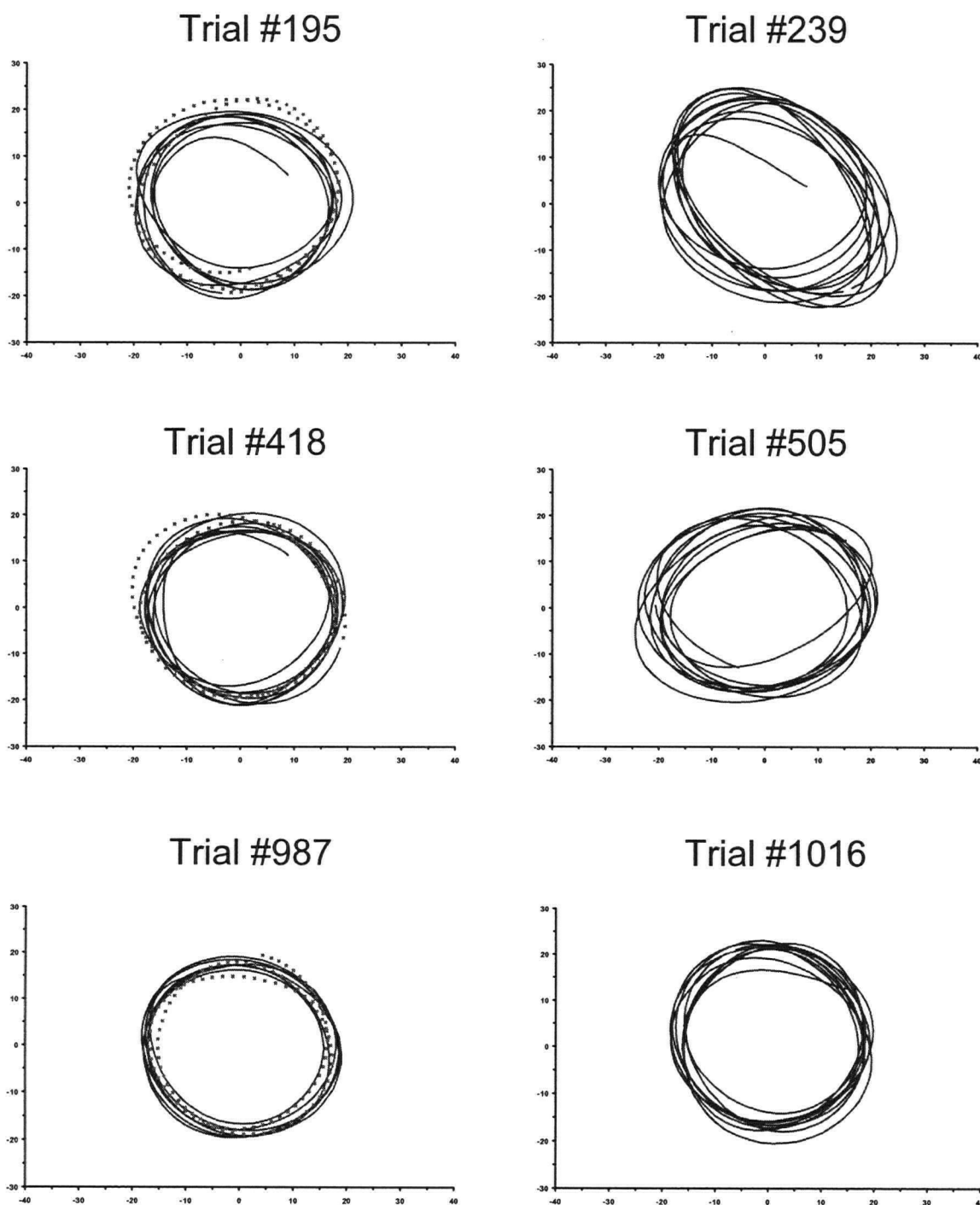


Figure 1.13. Individual trial data displayed as Lissajous figures for Participant 5. The left panel illustrates select acquisition trials whereby the solid line represents the vision segment, and the dotted line represents the no-vision segment. The right panel illustrates select no-feedback transfer trials (x-axis = right forearm displacement, y-axis = left forearm displacement).



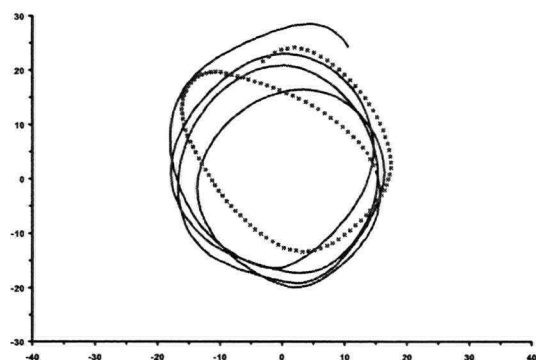
learning in the no-feedback transfer condition (right panel), performance of 90° RP deviated towards anti-phase as evidenced by the leftward-leaning elliptical shape of the pattern. However, with practice, the participant was able to overcome this tendency and performance under the no-feedback transfer condition improved in accuracy and stability to resemble the participants' performance in acquisition by the end of the test condition on Day 10. In contrast, several participants were unable to overcome the influence of pre-existing coordination tendencies whenever visual feedback was unavailable to guide performance. This is illustrated in Figure 1.14 for a representative participant. By Day 10, the participant was able to produce the relative phasing of the required pattern with considerable accuracy and stability when concurrent visual feedback was available, but could not overcome the influence of anti-phase with its removal for the last 3 s of the trial (left panel). Moreover, severe performance decrements were observed when the participant was required to perform under transfer conditions. Without relative motion feedback, the individual was unable to perform an accurate and consistent 90° RP pattern. Clearly, these figures demonstrate that removal of vision did not have the same lasting effects on performance for all participants.

Question 3: Did Extended Practice on a Bimanual Coordination Task Reduce and Eventually Eliminate Dual-Task Interference?

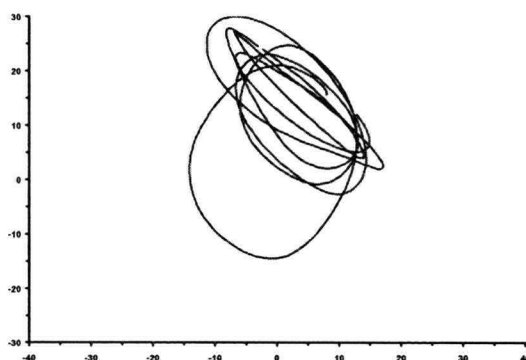
Probe-RT during Acquisition. The primary aim of this investigation was to examine the impact of practice on the attention demands of performing a 90° relative phase pattern of coordination. As such, participants were instructed to allocate attentional priority to performance of the 90° coordination pattern even if performance on the secondary RT task decreased. Maintaining primary task performance in the dual (or loaded) condition is essential if changes in secondary task performance are to be used to assess attentional characteristics of the primary task. In the dual-task condition, deterioration of performance on the 90° out-of-phase task would indicate that participants were trading off attention from the coordination task to the probe task to improve probe-RT performance (see Abernethy, 1988).

Figure 1.14. Individual trial data displayed as Lissajous figures for Participant 2. The left panel illustrates select acquisition trials whereby the solid line represents the vision segment, and the dotted line represents the no-vision segment. The right panel illustrates select no-feedback transfer trials (x-axis = right forearm displacement, y-axis = left forearm displacement).

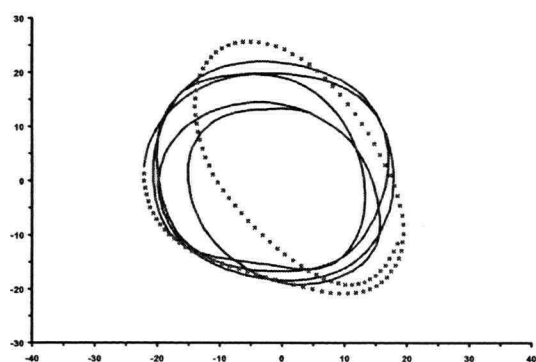
Trial #200



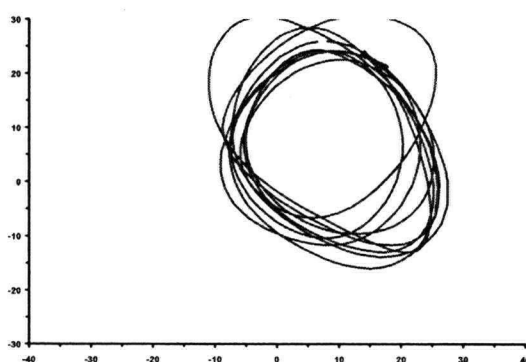
Trial #239



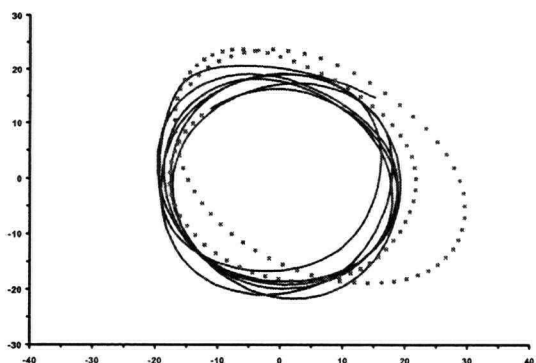
Trial #420



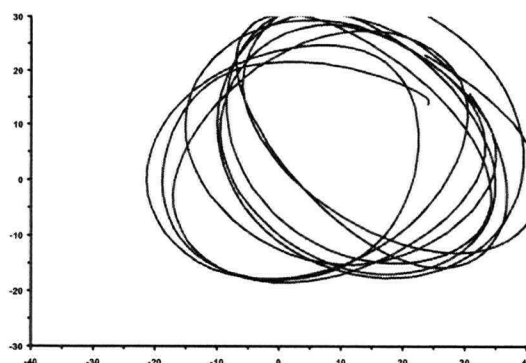
Trial #508



Trial # 950



Trial #1020



A preliminary analysis was conducted to verify that the performance of the 90° out-of-phase task was not affected by introduction of the secondary probe. Figure 1.15 illustrates the relationship between RMSE and trial number under no-probe and probe conditions across ten days of acquisition for the vision segment of the trial in a representative participant. A no-probe trial refers to baseline trials where participants were instructed that no probe could occur ($n = 100$), and catch trials where participants were instructed that there was a potential for the probe to occur, but no probe was ever introduced ($n = 540$). A probe trial refers to the loaded condition ($n = 360$). This figure reveals that there was a curvilinear reduction in RMSE with increasing trial number. This figure also reveals that there was no systematic difference in RMSE between no-probe and probe conditions, indicating that the probe condition did not adversely affect performance. Figure 1.16 illustrates the relationship between RMSE and trial during the 3 s no-vision trial segment. Visual inspection also reveals that there was no systematic difference between probe and no-probe conditions. Similar results were found for all participants in this investigation.

The participants' data were further analysed by calculating mean RMSE for both no-probe and probe conditions in each acquisition session, and submitted to a Trial Type (no-probe, probe) \times Day (9) repeated measures ANOVA. No significant differences were found for trial type ($p = .904$). Mean RMSE was 13.2° regardless of whether participants received or did not receive an auditory probe while performing a bimanual coordination task requiring a phase offset of 90°.

On all probe trials, a second analysis was conducted to determine whether performance before a probe was any different than performance following a probe. When the auditory stimulus occurred during the 8.5 s segment of the trial, RMSE was computed for 1 cycle preceding the stimulus (pre-probe) and for 1 cycle immediately following the stimulus (post-probe). These data were then submitted to a Time (pre-probe, post-probe) \times Day (9) repeated measures ANOVA. Analysis was constrained to the 8.5 s trial segment because of the significant main effect reported in Question 2 for the segment factor. Post-probe movement cycles commencing in the vision segment, but ending in the no-vision segment were also excluded from

Figure 1.15. Curvilinear (polynomial) relationship between RMSE and trial number under no-probe and probe conditions for the vision segment of a representative participant.

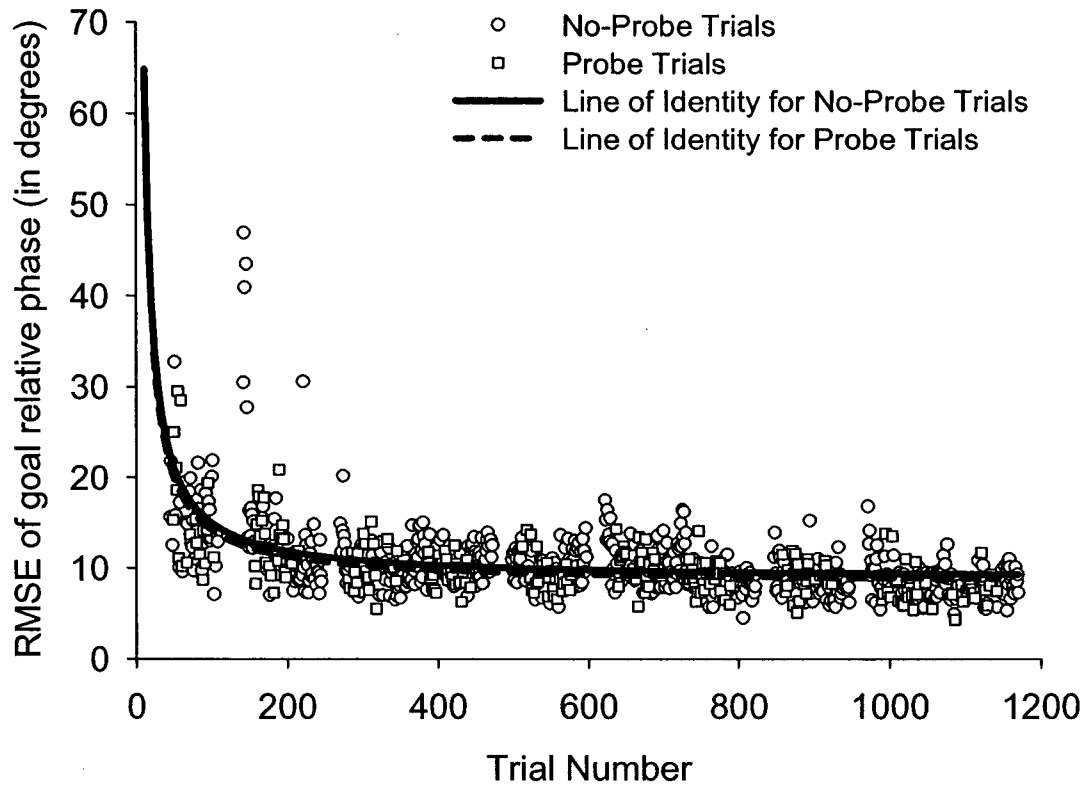
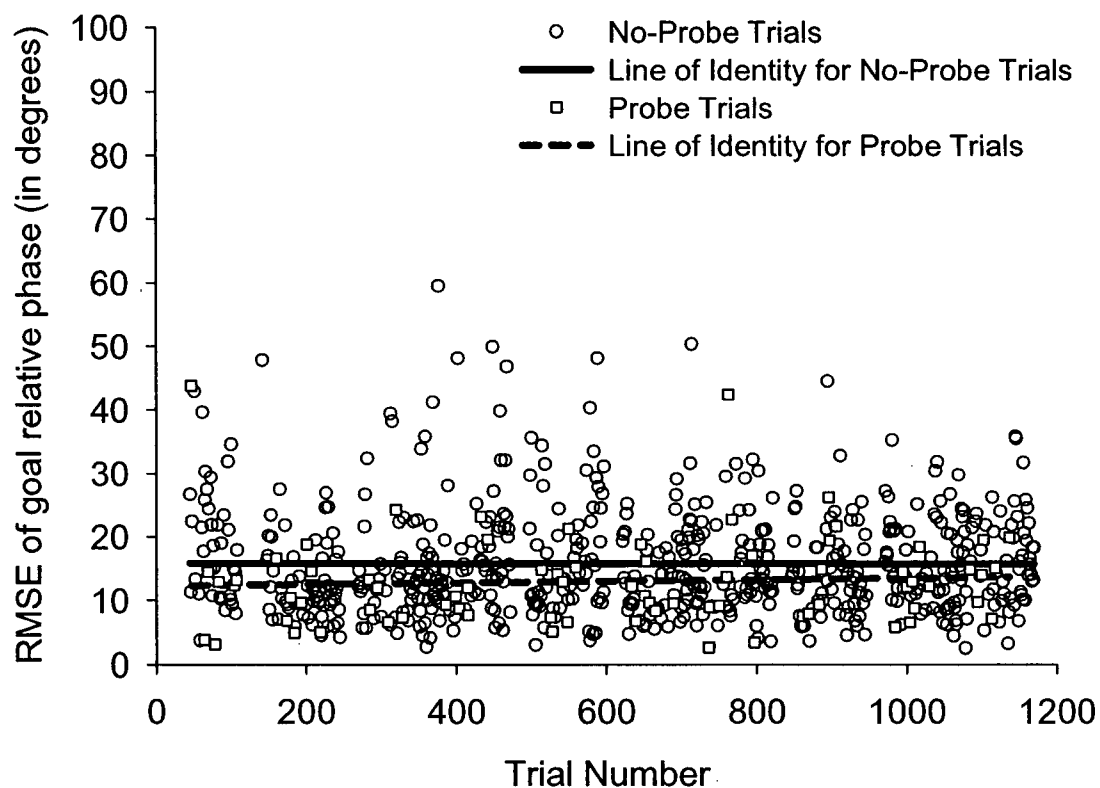


Figure 1.16. Relationship between RMSE and trial number under no-probe and probe conditions for the no-vision trial segment of a representative participant.



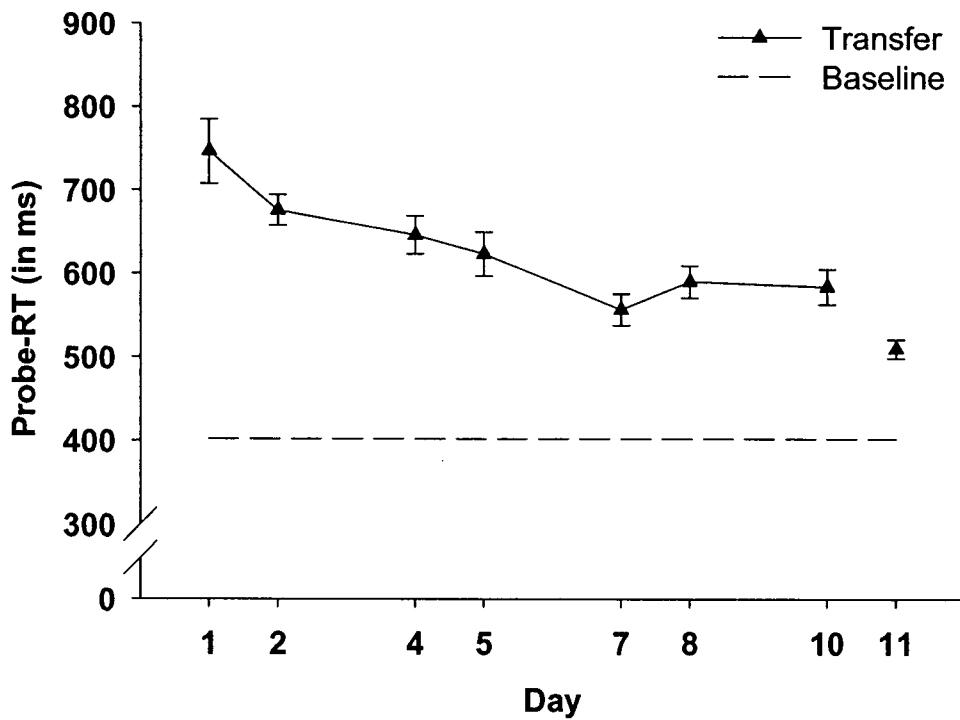
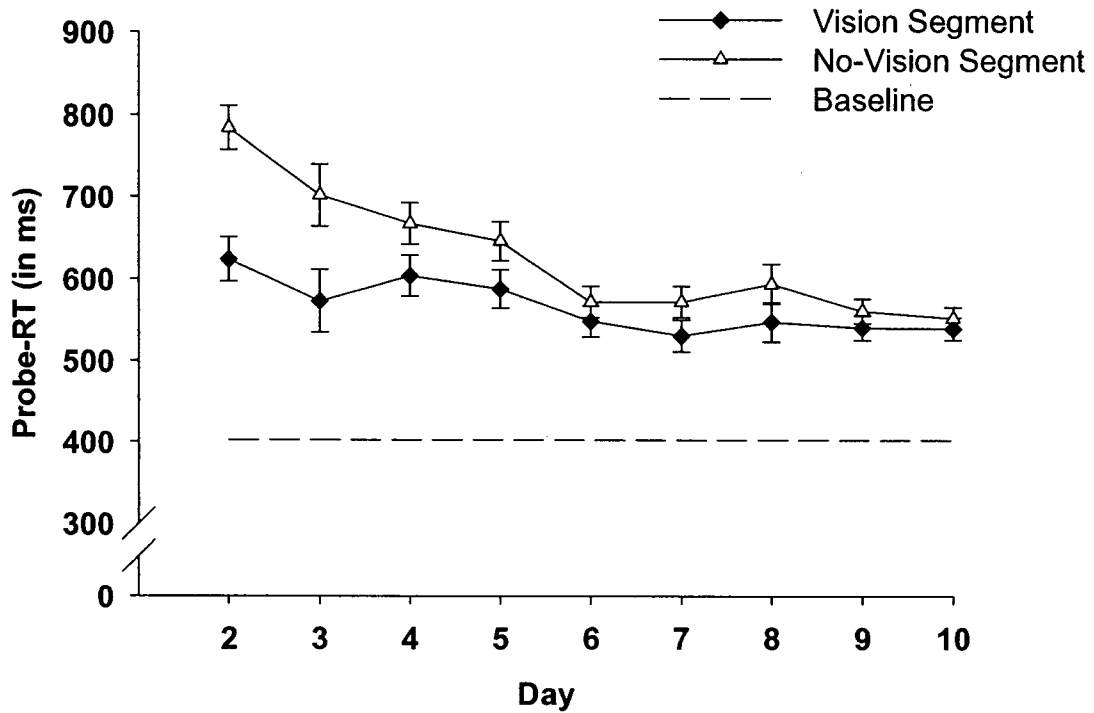
the analysis. Results revealed no significant differences in RMSE prior to and following an auditory probe ($p = .490$). These findings suggest that participants maintained performance on the 90° out-of-phase task and did not trade-off attention from the coordination task to improve secondary task probe-RT.

Following preliminary analysis, the probe data were subjected to a Condition (probe-RT, baseline RT) x Day (9) x Segment (vision, no-vision) x Probe Position (4) analysis of variance (ANOVA), with repeated measures on all factors. The mean reaction time of pre- and post-test measures were used for all cells of the baseline condition in the ANOVA (see data analysis).

Probe reaction times elicited during acquisition are illustrated in Figure 1.17 (top panel) for each trial segment. A significant three-way interaction emerged, $F(8, 40) = 5.80$, $p = .0001$, for condition x day x segment. Probe-RT was significantly slower during the no-vision segment ($M = 628$ ms, $SD = 137$ ms) than during the vision segment ($M = 566$ ms, $SD = 82$ ms). However, this difference decreased with practice. On Day 2, probe-RT during no-vision was 161 ms slower than during vision, but only 13 ms slower by Day 10. Findings also revealed that probe-RT was significantly faster when responding to the auditory probe alone than when responding while performing the 90° out-of phase task. Although Probe-RT decreased with practice, it did not reach baseline levels ($M = 402$ ms, $SD = 58$ ms) even after ten days of acquisition (Day 10: $M = 546$ ms, $SD = 67$ ms). There was no significant main effect for probe position ($p = .169$).

These findings suggest that practice resulted in a general decrease in dual-task interference. However, probe-RT did not reach baseline RT even after 1, 000 acquisition trials. One explanation for the present findings is that the amount of practice was not sufficient to produce an automatic response (even though participants engaged in a substantial number of practice trials of the 90° RP task). Earlier analysis of our data (Question 1) shows that performance of the coordination pattern continued to improve throughout learning (refer back to Figure 1.8 for an example). This is an important finding because as long as learning takes place and motor performance continues to improve, Blischke (1998) predicts the persistence of dual-task interference. Although dual-task interference was reduced in the present

Figure 1.17. Mean probe-RT for acquisition (top panel) and transfer (bottom panel) plotted as a function of day and compared to baseline RT ($M = 402$ ms) (Error bars = SEM).



investigation, it was not eliminated despite the extended and highly specific nature of practice.

Probe-RT during Transfer. Probe-RT collected under no-feedback transfer trials were submitted to a Condition (transfer probe-RT, baseline RT) x Day (1, 2, 4, 5, 7, 8, 10, 11) x Probe Position (4) ANOVA, with repeated measures on all factors. Probe reaction times elicited during transfer are displayed in Figure 1.17 (bottom panel). Results revealed a significant interaction effect for condition x day, $F(7, 35) = 9.74$, $p = .0000$. Probe-RT improved across days (Day 1: $M = 746$ ms, $SD = 188$ ms vs. Day 11: $M = 510$ ms, $SD = 56$ ms), but never reached baseline RT ($M = 402$ ms, $SD = 58$ ms). Post-hoc analysis showed that baseline RT was significantly faster in comparison to probe-RT collected on each day of transfer. There was no main effect for probe position ($p = .921$). These data indicate that dual-task interference continued to persist in transfer conditions, even after repeated exposure to performing the 90° out-of-phase task in the absence of continuous on-line visual feedback.

General Discussion

In the past, the probe-RT technique has been used extensively to investigate attention demands during the execution of simple-laboratory movement tasks (e.g., Eills, 1973; Posner & Keele, 1969) and, more recently, in real-world sporting tasks (e.g., Castiello & Umiltá, 1988; Prezuhy & Etnier, 2001; Rose & Christina, 1990). The present line of investigation sought to explore the attention requirements demanded by a bimanual coordination task over 1, 000 practice trials. Although dual-task interference was reduced, we found that bimanual coordination tasks continue to demand some form of attention even after extended periods of task-specific practice. Our data support recent views of automaticity, which hold that attention is still involved at high levels of performance (e.g., Logan, 1988) and that elimination of dual-task interference is unlikely achievable, even after prolonged durations of training (e.g., Ahissar et al., 2001). That is, dual-task interference may persist as long as learning takes place and motor performance continues to improve

(Blischke, 1998). Although improvements in performance are generally greatest at the early stages of learning, it is well documented that further practice continues to yield gains in performance (see Snoddy, 1926, power law of practice). For example, Crossman (1959) reported small performance improvements in the task of cigar-rolling by workers who had made over 10 million cigars and possessed seven years of task experience. In the present investigation, performance of the 90° out-of-phase pattern improved throughout the duration of the experiment, although gains exhibited at the end of practice were smaller than the gains displayed at the beginning. Given even more practice trials, it is likely improvements in performance would have continued.

Other investigators have recently reported that cognitive involvement is required to maintain stability of bimanual coordination tasks intrinsic to the system. For example, in-phase and anti-phase modes of coordination may be intentionally stabilized in a dual-task setting by giving attentional priority to the coordination task. Although improvement occurs at the behavioural level, the volitional stabilization of the pattern increases the coordinative activity of the central nervous system, leading to a trade-off between relative phase variability and RT (Temprado, Zanone, Monno, & Laurent, 1999) (see Experiment 4 in this dissertation). In related literature, experiments examining the coordination of walking have revealed that regulating gait also incurs a cost at the central level. Normal gait control of walking has been investigated because it is often considered to be an automatic process given the extensive level of practice it receives across the lifespan. Regardless of the relative ease with which we manage bipedal walking, evidence shows that gait control does not operate automatically but requires attention for movement control. For example, dual-task data have shown an increased attentional cost for walking when compared to standing and sitting (Bardy & Laurent, 1991; Lajoie, Teasdale, Bard, & Fleury, 1993), as well as secondary-task interference to gait control when a concurrent cognitive task is introduced (Evbersbach, Dimitrijevic, & Poewe, 1995). As such, it appears the performance of fundamental motor skills and tasks requiring bimanual coordination, as suggested by the present investigation, demand at least a minimal level of cognitive control for successful execution.

An important feature of the present investigation was the use of a self-directed learning approach. Participants were provided no instructions from the experimenter on how to move their limbs to produce the criterion pattern, nor did the experimenter intervene during the learning process to interpret or direct the learner's performance. For example, the experimenter provided no potential strategies to the learner, nor aided the performer in the interpretation of concurrent and terminal feedback. In this manner, the individual was left to his or her own devices to find an optimal solution to the motor problem at hand. This procedure is different than the methods implemented in many learning studies examining the acquisition of bimanual coordination. In these investigations, the experimenter often provides instructions or demonstrations as to how to produce the criterion pattern, or aids in interpretation of any feedback provided the performer throughout the learning process (e.g., Hodges & Franks, 2002; Hodges & Lee, 1999). Although these methods may be important for answering certain questions about the learning process, they may also bias the performer or even constrain the search for optimal learning solutions specifically suited to the individual. For example, experimenter-driven instructions and demonstrations are often very prescriptive in nature, and do not consider the capabilities or movement tendencies each individual brings with him or her to the learning environment; yet, the differences between people in the strength of underlying coordination tendencies might necessitate the use of different instructional techniques for skill acquisition. In the present investigation, participants were left to their own devices to discover how to break away from existing coordination tendencies and incorporate a new phasing pattern into their movement repertoire. In lieu of specific instructions and movement demonstrations on how to produce the required pattern, on-line relative motion feedback and terminal feedback were used by participants to generate a variety of solutions to the problem in a trial and error method of learning.

The provision of continuous on-line visual feedback has been shown to be a powerful source of information for the acquisition of new bimanual coordination patterns (Lee et al., 1995). Relative motion feedback facilitates skill acquisition by demonstrating the properties and relationships inherent within a task, which specify

how the system can be controlled. The present data suggest that continuous on-line visual feedback had a critical impact on performance. Some performers developed a control strategy that was dependent on their capability to use the continuous on-line visual feedback to guide performance. When visual feedback was removed, these participants exhibited difficulties in overcoming the attraction of preferred coordination modes and were unable to maintain stability of the new relative phasing pattern. This influence was evident even at late stages of learning. In the present experiment, it is possible that the extensive use of on-line visual feedback influenced the individual's capability to use information sources other than vision to make the same gains in performance under conditions of withdrawal. Although the provision of relative motion feedback is a powerful source of information and potentially important learning aid in the acquisition of coordinated movement, these findings identify potential pitfalls when it is provided for extensive periods of practice. Further work examining ways to overcome the influence of preferred coordination tendencies, as well as the consequences of various forms of feedback, is clearly warranted.

Chapter Footnotes

1. According to Abernethy (1993), there are a number of methodological issues that must be taken into consideration if a secondary-task paradigm is to provide valid measures of attentional cost (also see Abernethy, 1988 for a review). The task of interest in the present line of investigation was the acquisition of a 90° RP pattern, which became the primary task. Therefore, our first methodological concern involved selecting an appropriate secondary task (see Ogden, Levine, & Eisner, 1979 for a review). To assess the degree of 'free attentional space' available after the attentional needs of the primary task have been met, care was taken to remove any structural interference between the primary and secondary task. This was accomplished by selecting a secondary task that utilized different sensory and response modalities than the primary task. We selected a probe-RT technique whereby the participant responded to the auditory stimuli by initiating a

vocal response. Therefore, the primary and secondary tasks did not use common input or output processes. To further eliminate the potential for structural interference, participants were permitted to move at their own pace. This contrasts typical methodological protocol in that participants are commonly required to move in time with an auditory metronome that beeps at a particular frequency. A second rationale for selecting probe-RT as the secondary task was because it was a discrete measure. When performing a continuous secondary task, there is a potential for errors to accumulate. As such, it becomes difficult to equate attentional fluctuations with specific phases of the primary task. In the present line of investigation, we were interested in attention demands at points of critical limb reversal points, and therefore, required a discrete measure such as probe-RT.

A second methodological concern relates to probe frequency. Salmoni, Sullivan, and Starkes (1976) have demonstrated that the shape of a curve relating RT to probe position in a movement is different depending on the probe frequency employed. For a simple positioning movement, a V-shaped curve (i.e., probe-RT elevated at movement initiation and termination) results when using a probe frequency of two-thirds (see Posner & Keele, 1969), while a negatively accelerating curve (i.e., probe-RT elevated at movement initiation) is produced when a probe occurs on every trial (see Ellis, 1973). If the experimenter probes too frequently, participants may begin to anticipate the onset of a stimulus. As a consequence, RT to the probe can be considerably enhanced. In addition, the individual may begin to see the primary and secondary tasks as one. This is problematic in that measures of RT no longer give an accurate description of the underlying attention demands of the task of interest. In contrast, if the experimenter probes too infrequently, the individual may be taken by surprise and probe-RT is artificially elevated. Taking the issues presented by Salmoni et al. into consideration, we elected to use a probe frequency of approximately one-third.

2. Prior to, and at the end of the final day of testing, participants performed a bimanual coordination scan as discussed in *Appendix A - Motor Learning and Dynamic Pattern Theory*. To obtain a picture of each participant's landscape before and after the learning episodes, individuals were scanned in a continuous manner. These data are not presented here because methodological issues have arisen concerning the use of this procedure for scanning an individual's attractor landscape, which is further discussed in Appendix B (*Using the Scanning Procedure for Mapping Dynamical Landscapes: Methodological Implications*).
3. A retention test is a common procedure used in motor learning to assess how much of the skill has been retained following an interval of time after practice has ceased. Typically, researchers employed this type of test by requiring a person to perform in the absence of augmented feedback. Removal of augmented feedback was deemed acceptable because the practiced skill was performed during the test. In recent years, some individuals have argued that altering availability of augmented feedback changes the context in which the learner must perform the skill. Therefore, a test that requires an individual to perform without augmented feedback should be classified as a transfer test (not a retention test) because the learner performs the practiced skill in a context different from the learning context (see Magill, 2004, p. 200). In the present experiment, any test requiring the removal of augmented feedback was referred to as a transfer test.
4. $F = \tan^{-1}[(dX_R/dt)/X_R] - \tan^{-1}[(dX_L/dt)/X_L]$, where F = relative phase between the limbs, X is the position of the limb within a cycle re-scaled to the interval $[-1,1]$, (dX/dt) refers to normalized instantaneous velocity, and R and L are the right and left limbs (adapted from Scholz & Kelso, 1989, p. 129).
5. Mean baseline RT across participants was 402 ms, which is elevated in comparison to typical voluntary reaction time responses exhibiting latencies as

low as 120 to 180 ms. However, vocal probe reaction times are found to be longer than manual probe reaction times. For example, Starkes (1987) showed that simple RT requiring a vocal response was over 300 ms, while simple manual probe RT was less than 250 ms. Furthermore, findings revealed that mean vocal RT was elevated in dual-task conditions when compared to simple vocal RT displaying values ranging from 531 ms to 679 ms for three different probe positions. More recently, Bourdin, Nougier, & Teasdale (1997) used a dual-task paradigm to examine the attentional demands of grasping movements in a rock climbing situation. The secondary task required responding vocally (say "top") as fast as possible to an auditory stimulus. Probe-RT for different levels of reaching and hold complexity ranged from 416 ms to 582 ms. The results of Starkes (1987) and Bourdin et al. (1997) suggest that vocal probe-RT values are comparable in the present experiment.

6. Percent change from Day 2 was calculated using the following formula: $-1 * (\text{Day } x - \text{Day } 2) / \text{Day } 2 * 100$.

CHAPTER II

EXPERIMENT 2

Effects of Reducing Continuous On-line Visual Feedback on Attention Demands and Extended Learning of a New Bimanual Coordination Task

Introduction

Studies in interlimb coordination have shown that the majority of individuals demonstrate bi-stable dynamics prior to practice. Bi-stability is described as the tendency to move the limbs in one of two modes of coordination, called in-phase and anti-phase, which are defined by the relative timing of the two limbs. In-phase movements correspond to synchronized flexion and extension of the limbs; while, anti-phase movements are characterized by flexion and extension of the limbs in alternation (Kelso, 1984). In addition to these pre-existing behaviours, new patterns can emerge with relative stability and accuracy as a function of practice. For example, individuals can learn to coordinate their limbs with a phase offset of 90° , whereby one limb leads the other by one-quarter of a movement cycle in time (e.g., Fontaine, Lee, & Swinnen, 1997; Lee, Swinnen, & Verschueren, 1995; Wenderoth & Bock, 2001; Zanone & Kelso, 1992, 1997). For most individuals, the 90° out-of-phase task is not part of their pre-existing movement repertoire. Therefore, substantial practice is needed to obtain accurate and stable levels of performance. The addition of new phasing patterns into an existing movement repertoire changes the dynamic stability of bimanual coordination from a bi-stable regime to a tri- or multi-stable regime (see Fontaine et al., 1997; Smethurst & Carson, 2001; Zanone & Kelso, 1992 for discussion on dynamic stability).

Most important to the acquisition of new motor patterns is the finding that pre-existing coordination tendencies appear to disrupt the learning process. At early stages of learning, attempts to coordinate the limbs in a 90° offset usually results in performance of the anti-phase pattern (or less frequently) the in-phase pattern (e.g., Fontaine et al., 1997; Lee et al., 1995; Zanone & Kelso, 1997). For some individuals, these biases continue even after considerable practice (see Experiment 1).

Therefore, a major difficulty of the learning process is inhibiting the strong tendency

to perform more stable, preferred patterns. This includes breaking away from pre-practice behaviours, as well as resisting the influence of intrinsic patterns when task conditions change. Determining practice variables that will decrease the effects of pre-practice behaviours on the acquisition of new coordination skills has obvious importance from both a theoretical and practical perspective.

To break away from pre-existing coordination biases, individuals may use a number of different information sources. One type of information that has demonstrated its effectiveness for acquiring the 90° out-of-phase task is the provision of continuous on-line visual feedback (e.g., Lee et al., 1995; Swinnen et al., 1997). This mode of augmented feedback can be presented to the learner in 2-dimensional form on a computer monitor by orthogonally plotting displacements of the left and right limbs in real-time. When correctly moving the limbs in a phase offset of 90°, the resulting relative motion plot (also referred to as a Lissajous figure) corresponds to a circle. In contrast, in-phase motions produce straight, diagonal lines between the lower left and upper right corners of the monitor, while anti-phase movements produce straight lines extending from the lower right to the upper left corner. To specify the task goal during the learning process, a criterion template is displayed on the monitor, and the displacements of the right and left limbs are superimposed onto the template. In addition to the task goal, the relative motion plot provides learners with non-prescriptive feedback alerting them to the exact nature and extent of their movement. This information may then be used to guide subsequent performance attempts. Relative motion feedback is a valuable source of information because it demonstrates the properties and relationships inherent within the task, which specify how the system can be controlled.

One issue that has recently surfaced is whether individuals become increasingly dependent on relative motion feedback to guide coordination movements as learning progresses. This concern arises from empirical evidence, which suggests that augmented feedback provides strong informational support when it is available, but degrades performance when it is removed or task conditions change (see Salmoni, Schmidt, & Walter, 1984). This negative learning effect is reported to be especially prevalent when augmented feedback is provided

concurrently with practice of the movement (Schmidt & Wulf, 1997; van der Linden, Carraugh, & Greene, 1993; Verschueren, Swinnen, Dom, & De Weerd, 1997; Winstein, Pohl, Cardinale, Green, Scholtz, & Waters, 1996). Rather than directing attention to the critical proprioceptive features of the task, the learner specifically focuses on the augmented feedback. As such, an internal representation of the movement is derived from feedback extrinsic to the system, rather than on important task-intrinsic information. Consequently, performance is disrupted when concurrent feedback is unavailable because the learner is unable to effectively process intrinsic feedback sources for execution of the movement task.

In Experiment 1, we examined how practice affected the production and stability of the 90° out-of-phase task. To facilitate acquisition, participants received continuous on-line visual feedback for the first 10 s of each 13 s trial. This feedback was removed for the final 3 s of the trial, followed by terminal feedback displaying the just-performed no-vision segment in the form of a Lissajous trace. Findings revealed that relative motion feedback had a critical impact on performance. In the presence of feedback, individuals were successful in producing the required phasing pattern. However, when visual feedback was removed for the final 3 s of the trial, several participants exhibited a strong bias towards the more preferred motor pattern of anti-phase. Even after a considerable number of practice trials (i.e., 1,000 trials), the inability to inhibit or overcome the influence of the anti-phase mode of coordination was evident. Effects of pre-existing coordination tendencies were also apparent when examining performance of 90° RP under a no-feedback transfer condition. Performance deteriorated as demonstrated by decreases in both accuracy and stability of the required phase relationship. It is possible that providing relative motion feedback for a significant portion of each and every trial may have prevented some individuals from processing critical proprioceptive features of the task. As a consequence, these individuals were unable to modify the influence of pre-practice behaviours and produce the required movement successfully when visual feedback was no longer available to guide performance. Therefore, the first objective of the present investigation was to further examine the role of relative motion feedback for learning a 90° RP bimanual coordination task. More specifically, we employed the

same experimental design as described in Experiment 1 with one exception. Instead of receiving relative motion feedback for 10 s of the trial, participants received concurrent visual feedback for only initial calibration to the computer monitor (1.5 s) and the final (3 s) segment of the trial. This means that relative motion feedback was removed for the middle (8.5 s) segment¹. The purpose of providing relative motion feedback for only a small trial portion was to encourage attention to critical sensory sources intrinsic to the task, thereby facilitating performance of the 90° out-of-phase task when feedback became unavailable to guide movement execution.

Limiting the availability of visual feedback, in comparison to Experiment 1, was expected to influence the learning process in several ways. First, it was predicted that participants would demonstrate a slower rate of acquisition. After initial calibration to the computer monitor, individuals were unable to check the accuracy or consistency of their movement trace against the criterion until the end of the trial. Most important, however, was that once relative motion feedback was available in real-time, the participant was only provided 3 s to make on-line corrections. Given that participants received no specific instructions regarding how to produce the required phasing pattern, information gleaned from provision of concurrent (and terminal) feedback were essential for "getting an idea of the movement" (see Gentile, 1972). Based on this rationale, it was also postulated that performance during the vision segment should be superior in comparison to the no-vision segment early in learning. However, differences between the two segments were expected to decrease as a function of practice.

With respect to performance under conditions of transfer, we postulated that a performance advantage would emerge in immediate and delayed no-feedback transfer conditions, as compared to the results of Experiment 1. This prediction was based on evidence from the investigation of unimanual discrete tasks, which suggest that learning is specific to the sources of sensory feedback available during practice. Referred to as the specificity of learning hypothesis (e.g., Proteau, Marteniuk, Girouard, & Dugas, 1987), this perspective proposes that sensory information made available to the performer during learning is integrated into a sensorimotor memory representation of the task. As the individual increases the

amount of practice with the sources of information, a dependency transpires. A consequence of this reliance is that performance may deteriorate when the individual is required to perform in a context where the sensory information is withdrawn. In contrast to our former investigation, the conditions of practice more closely matched the conditions of transfer. Therefore, when compared to the results of Experiment 1, participants were expected to perform the 90° pattern with less error and greater stability when continuous on-line visual feedback was withdrawn as an information source to guide the movement.

The second objective of the study was to continue our investigation into the attention demands of bimanual coordination. To assess the attentional costs of performing a 90° out-of-phase task we employed the same classic measure of discrete reaction time (RT) as described in Experiment 1. Considering the difficulties associated with learning a bimanual coordination task under conditions of limited instructions and feedback, it was hypothesized that practice would diminish attention demands of the 90° pattern, but elimination of dual-task interference was not expected in the present investigation.

Method

Participants

Informed consent was received from six self-professed right-handed individuals from a university population ($n = 4$ females; $n = 2$ males). The mean age of participants was 26.3 years ($SD = 2.7$, range = 23-31 years). All individuals were naïve to the purpose of the experiment and none had previous experience as a participant in a bimanual coordination investigation. Upon completion of the final session, all participants received remuneration. The experiment was carried out according to the ethical guidelines set by the University Behavioural Science Screening Committee for research involving human participants.

Apparatus and Tasks

The apparatus, as well as the primary and secondary tasks were the same as described in Experiment 1. The goal of the primary task was to learn to correctly

move the forearms in the horizontal plane to produce a 90° RP pattern of coordination. While performing the primary task, participants were required to emit a vocal response as quickly as possible if at any time a computer-generated auditory 'beep' occurred. The auditory tone was delivered at one of four possible probe positions: Probe A (Pr A), Probe B (Pr B), Probe C (Pr C), and Probe D (Pr D), which were also defined in the methods of Experiment 1.

Procedure

All procedures for the acquisition, immediate transfer, and delayed transfer phases of the present investigation were identical to Experiment 1 except for the amount of relative motion feedback provided during each acquisition session. Participants received visual feedback for the first 1.5 s of each trial, whereupon vision was removed and participants received no relative motion feedback for the next 8.5 s. At the 10 s mark, visual feedback was restored and remained on the screen for the final 3 s of the trial. At the completion of each trial, participants received terminal feedback of the just-performed no-vision (8.5 s) trial segment, which was superimposed over the criterion template and the orthogonal plot produced during the vision (3 s) segment of the trial. Each segment was plotted in different colours in the form of a Lissajous figure. Presenting vision at the beginning of the trial provided an opportunity for participants to calibrate the cursor to the computer screen and begin the 90° out-of-phase pattern. The experimenter provided no instructions regarding how to produce the required pattern prior to, or during the investigation.

Data Analyses

As outlined in Experiment 1, spatiotemporal differences between the limbs were determined using continuous measures of relative phase (RP). Performance of the 90° out-of-phase task was further quantified by calculating: root mean square error (RMSE) relative to the criterion goal, standard deviation around the mean relative phase (SD of RP), and cycle frequency. The secondary task probe technique (probe-RT) was used to determine attention demands of the 90° relative

phase task. All post-hoc comparisons were performed using the Tukey HSD procedure. The level adopted for achievement of statistical significance was $p \leq .05$.

Results

The results are presented according to four main questions, specifically: (1) Did performance of the required pattern improve with practice? (2) Did performance differences appear between segments? (3) Did a performance advantage emerge in no-feedback transfer tests for learners receiving limited relative motion feedback during acquisition (as compared to Experiment 1)? and finally, (4) Did extended practice on a bimanual coordination task reduce and eventually eliminate dual-task interference?

Question 1: Did Performance of the Required Pattern Improve with Practice?

Changes in Pattern Accuracy and Stability across Acquisition. A $9 \times 2 \times 5$ (Day x Segment x Block) ANOVA, with repeated measures on all factors was administered to examine the impact of practice on the acquisition of the 90° out-of-phase coordination task for both RMSE and SD of RP. The segment variable referred to the first 8.5 s no-vision segment and the final 3 s vision segment. This section will focus on the results for day and block, while Question 2 will discuss 90° RP performance with respect to segment. Day 1 was not included in the analysis because several participants moved so slowly they did not complete one full movement cycle within a trial (as previously discussed in Experiment 1).

Performance improved in accuracy as evidenced by main effects for day, $F(8, 40) = 4.92$, $p = .0002$, and block, $F(4, 20) = 10.20$, $p = .0001$. When compared to Day 2, RMSE improved by 9% on Day 3, 22% on Day 4, and 29% on Day 6. This trend continued as RMSE steadily improved from 39% on Day 7 to 49% on Day 10. Post-hoc analysis revealed that Block 5 ($M = 21.1^\circ$, $SD = 14.9^\circ$) was significantly more accurate than Blocks 1 ($M = 24.7^\circ$, $SD = 16.0^\circ$) and 2 ($M = 23.5^\circ$, $SD = 16.0^\circ$), while Blocks 3 ($M = 22.5^\circ$, $SD = 15.2^\circ$) and 4 ($M = 22.2^\circ$, $SD = 15.2^\circ$) were performed with greater accuracy when compared to Block 1. The performance

measure of RMSE and percent improvement scores are presented in the upper panel of Figures 2.1 and 2.2, respectively.

The 90° out-of-phase pattern also became more stable with increasing practice. This observation is supported by significant main effects for day, $F(8, 40) = 3.16$, $p = .007$, and block, $F(4, 20) = 5.58$, $p = .003$. Large decreases in pattern variability occurred from Day 2 to Day 3, as stability improved by 25%. Improvements in SD of RP continued until the end of acquisition as evidenced by further increases in stability from 33% on Day 4 to 39% on Day 6, and finally to 51% on the final day of acquisition, when compared to variability of the 90° out-of-phase task on Day 2. Performance of the 90° RP pattern was more stable in Blocks 3 ($M = 16.6^\circ$, $SD = 13.8^\circ$) and 5 ($M = 15.7^\circ$, $SD = 13.3^\circ$), in comparison to Block 1 ($M = 18.6^\circ$, $SD = 14.1^\circ$). Standard deviation of RP is presented in Figure 2.1 (lower panel), while percent improvement scores are illustrated in Figure 2.2 (lower panel).

Changes in Cycle Frequency across Acquisition. A $9 \times 2 \times 5$ (Day \times Segment \times Block) ANOVA, with repeated measures on all factors, revealed preferred rates of cycle frequency for the criterion task from Day 2 to Day 10 of acquisition. Results showed a significant main effect for Block, $F(4, 20) = 7.77$, $p = .001$, only. Preferred rate of cycle frequency increased and was significantly faster in Blocks 3 ($M = 0.726$ Hz), 4 ($M = 0.731$ Hz) and 5 ($M = 0.730$), when compared to cycle frequency in Block 1 ($M = 0.689$ Hz). Mean preferred rate of cycle frequency ranged from 0.4 Hz to 1.2 Hz. On average, participants performed approximately 9 cycles per trial, which was maintained across the final nine days of practice.

Performance of the 90° out-of-phase task improved with practice. These findings demonstrate that accuracy and stability of the criterion task improved across the time course of learning. Given more practice trials, it is likely improvements in performance of the 90° pattern would have continued. Interestingly, cycle frequency did not increase as a function of practice. Rather, participants generally maintained their selected cycle frequency for the duration of the experiment.

Figure 2.1. RMSE of goal relative phase (top panel) and SD of RP (bottom panel) across 9 days of acquisition (Error bars = SEM).

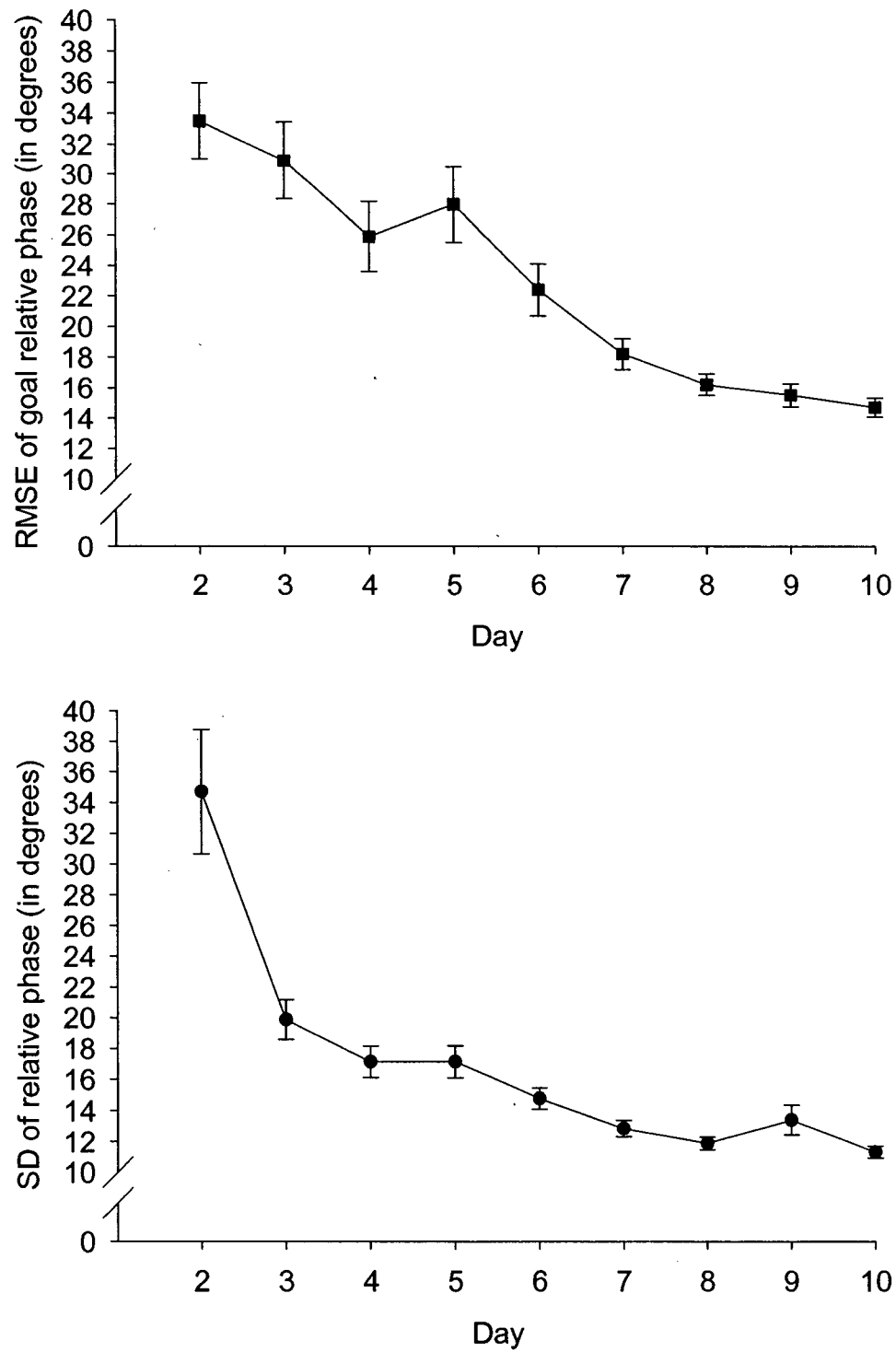
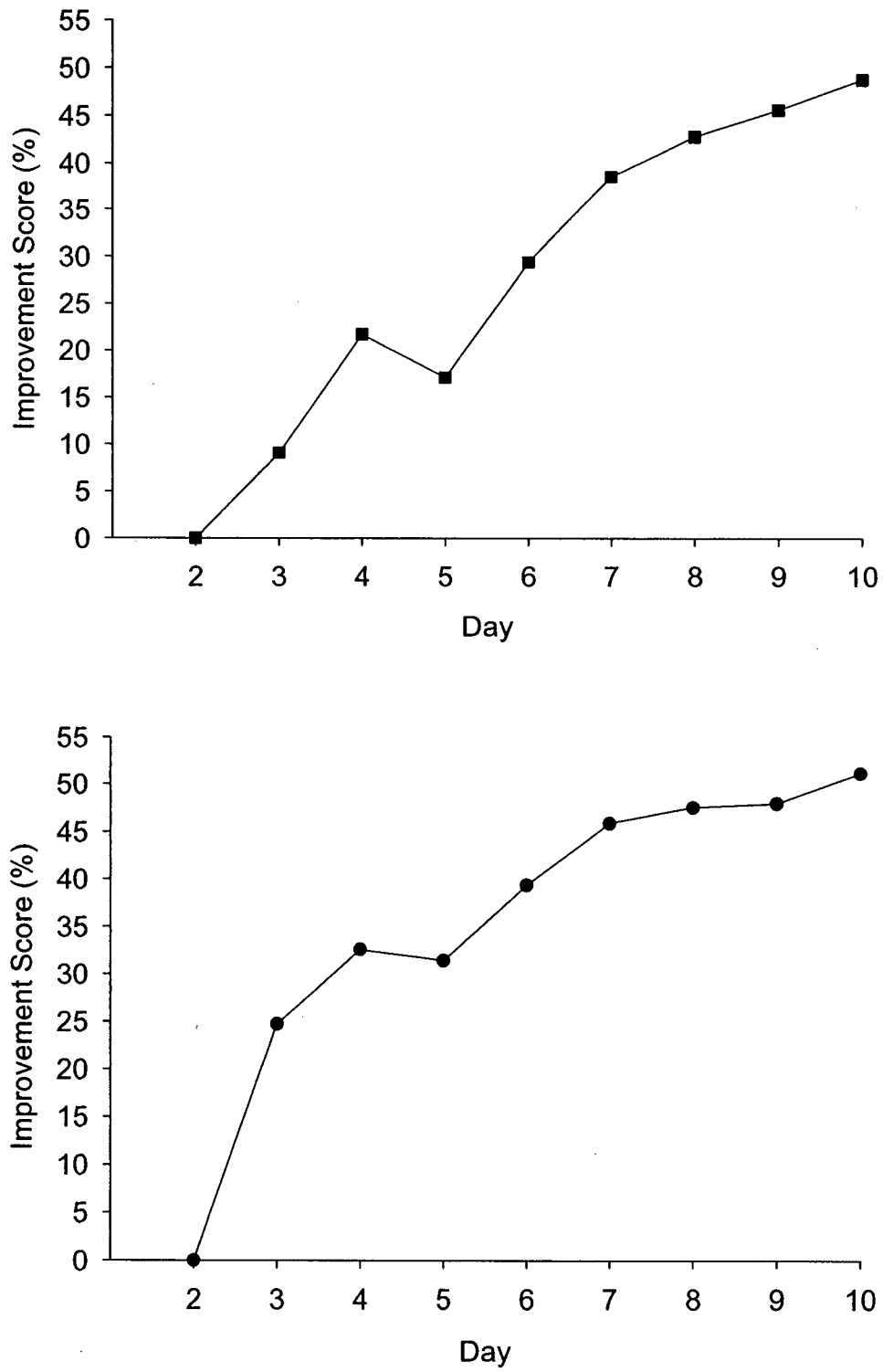


Figure 2.2. Percent Improvement from Day 2 for RMSE of goal relative phase (top panel) and SD of RP (bottom panel).



Question 2: Did Performance Differences Appear between Segments?

Changes in Pattern Accuracy and Stability across Acquisition. The $9 \times 2 \times 5$ (Day \times Segment \times Block) ANOVA (see Question 1) revealed that performance during the no-vision segment was generally less accurate when compared to performance under the vision condition ($\underline{M} = 25.6^\circ$ vs. 19.8° ; $\underline{SD} = 19.8^\circ$ vs. 11.7° , respectively), but did not reach statistical significance ($p = .076$). Accuracy of the bimanual coordination task continued to improve for both segments from Day 2 (\underline{M} No-Vision = 37.2° ; \underline{M} Vision = 30.0°) to the final day of acquisition (Day 10: \underline{M} No-Vision = 16.2° ; \underline{M} Vision = 13.2°). Performance of RMSE is illustrated in Figure 2.3 for the 8.5 s no-vision segment (left panel) and the 3 s vision segment (right panel).

Analysis of SD of RP showed a significant main effect for day, $F(1, 5) = 7.35$, $p = .042$. The 90° pattern was more stable in the presence of on-line visual feedback ($\underline{M} = 14.9^\circ$, $\underline{SD} = 11.9^\circ$) in comparison to performance under the no-vision condition ($\underline{M} = 19.2^\circ$, $\underline{SD} = 15.4^\circ$). Results also revealed a significant interaction effect for day and segment, $F(8, 40) = 2.46$, $p = .028$. This interaction effect occurred because a larger gain in pattern stability occurred from Day 2 to Day 3 for the no-vision segment when compared to the vision segment (\underline{M} improvement = 18.4° vs. 11.3° , respectively). Post-hoc analysis revealed that performance of the 90° RP task was not significantly different between segments after Day 2. The coordination pattern was performed with the lowest SD of RP on the final day of acquisition for both segments (Day 10: \underline{M} No-Vision = 12.6° ; \underline{M} Vision = 10.0°). Standard deviation of RP is illustrated in Figure 2.4 for the 8.5 s no-vision segment (left panel) and the 3 s vision segment (right panel).

Performance in Relation to the Criterion Pattern. Although the preceding results showed that differences in performance between the two segments decreased as a function of practice, it does not reveal the type of pattern the participants produced. That is, did participants learn to coordinate the limbs in a phase offset of 90° ? To determine performance in relation to the criterion pattern,

Figure 2.3. RMSE of goal relative phase for the no-vision (left panel) and the vision segment (right panel) across 9 days of acquisition (Error bars = SEM).

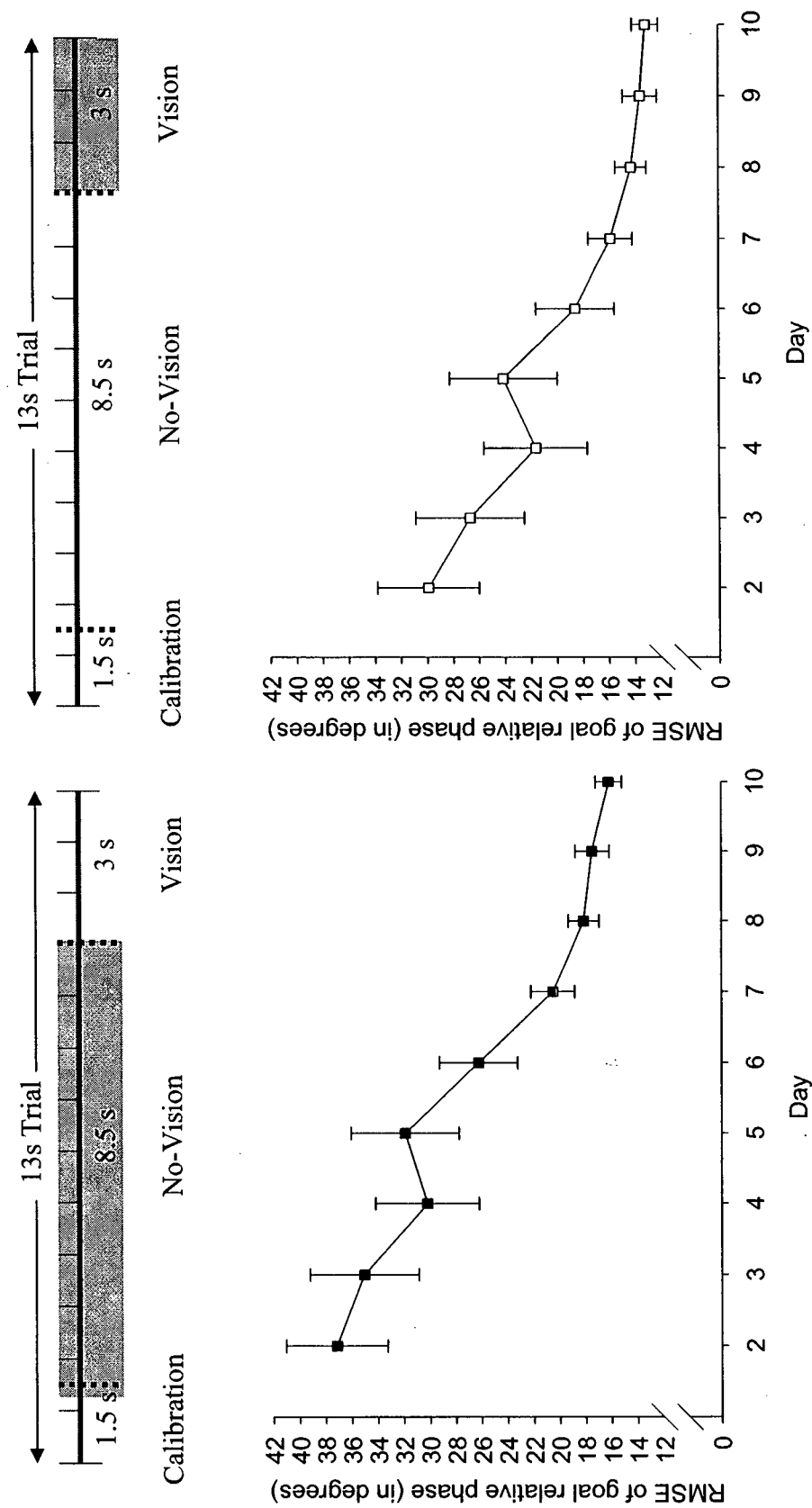
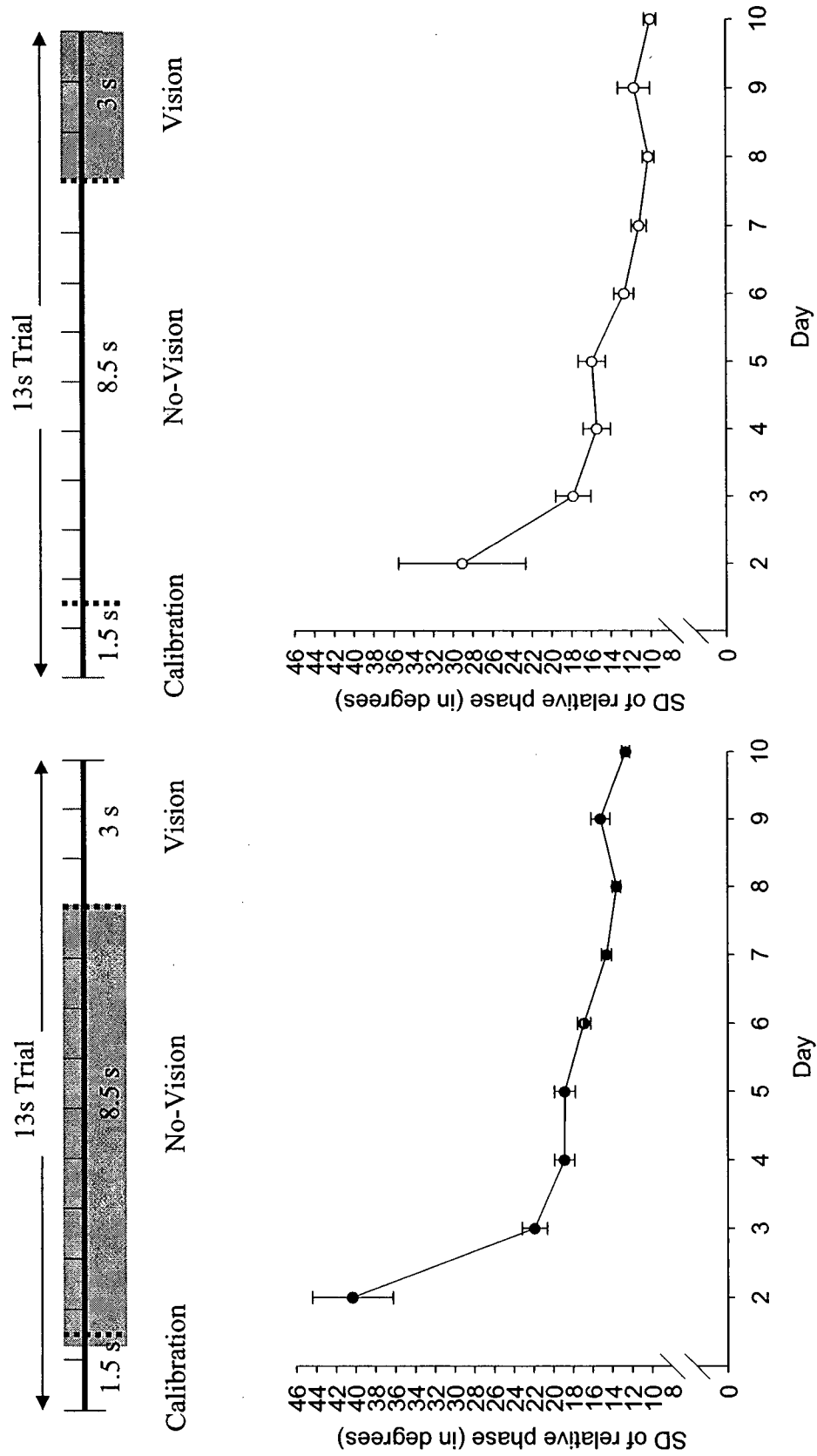


Figure 2.4. Standard deviation of relative phase for the no-vision (left panel) and the vision segment (right panel) across 9 days of acquisition (Error bars = SEM).

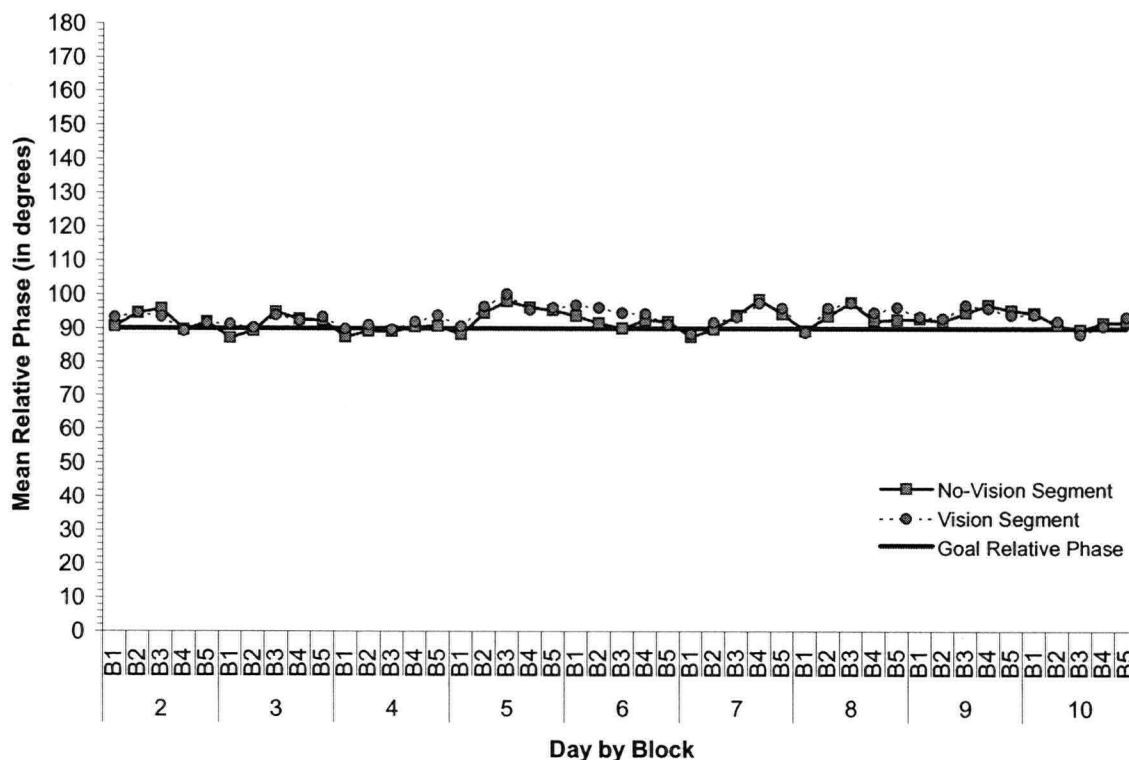


overall mean RP was examined. On Day 5, mean RP was 114° for the no-vision segment and 104° for the vision segment. By Day 10, this value was closer to the 90° RP criterion. The overall mean RP for the no-vision and vision segments were 96° and 94° , respectively. In general, participants learned to perform the 90° out-of-phase task within a bandwidth of $\pm 10^\circ$ of the required phasing relationship. However, learning progressions between participants varied widely.

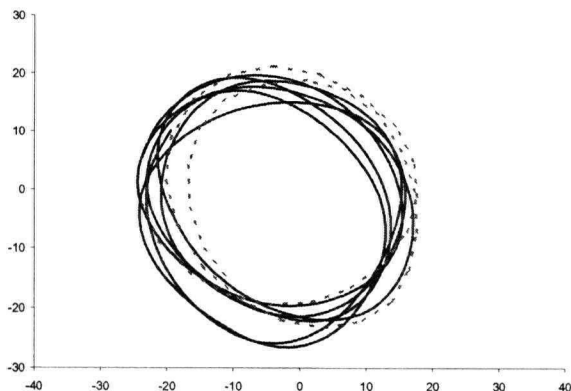
Individual Performance Data. With no instructions and a limited presentation of on-line visual feedback, a limb phasing of 90° was initially difficult for many participants to acquire. By the end of Day 1, only one participant was able to produce a phase offset of 90° under no-vision and vision conditions (Block 5, \bar{M} RP = 90° and 91° , respectively), while 2 of the 6 participants demonstrated a pattern of performance within $\pm 10^\circ$ of the criterion task for both segments. In contrast, the remaining 3 participants demonstrated a strong bias toward the anti-phase pattern and were unable to produce a circular pattern after 100 trials in either segment of the trial. In fact, for one participant, performance within $\pm 10^\circ$ of goal relative phase only emerged during the vision segment after 600 trials, and was finally achieved in the no-vision segment after 800 trials. To demonstrate the differences observed in individual progressions of learning, sample data have been provided for two participants in Figures 2.5 and 2.6. In the top panel, mean RP data have been plotted in blocks of 20 trials across learning. Both the no-vision and vision segments have been plotted on the same graph. In the bottom panel, select trials have been presented in the form of a Lissajous figure to represent the phasing relationship between the limbs in 2-dimensional form.

Figure 2.5 represents data from a participant who did not exhibit the same difficulty in learning the circle pattern as demonstrated by other participants. Performance within $\pm 10^\circ$ of the criterion was achieved on the first day of acquisition and maintained regardless of whether visual feedback was available or unavailable to guide performance. These data suggest that the individual was able to inhibit the attraction of intrinsic coordination tendencies and acquire a new phase relationship between the limbs. Providing 3 s of visual feedback, in addition to terminal feedback,

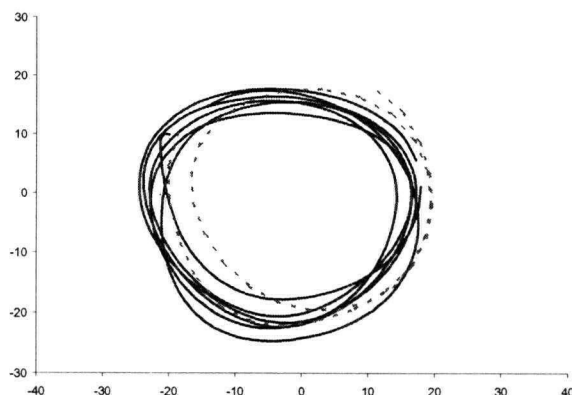
Figure 2.5. Mean RP for Participant 4 plotted in blocks of 20 trials across nine days of acquisition for the no-vision segment and the vision segment (top panel). Performance is also presented in the form of Lissajous figures for select trials (bottom panel). The solid line represents the no-vision segment and the dotted line represents the vision segment (x-axis = right forearm displacement; y-axis = left forearm displacement).



Day 3 Trial #250
No-Vision = 96° RP; Vision = 84° RP



Day 8 Trial #785
No-Vision = 91° RP; Vision = 91° RP

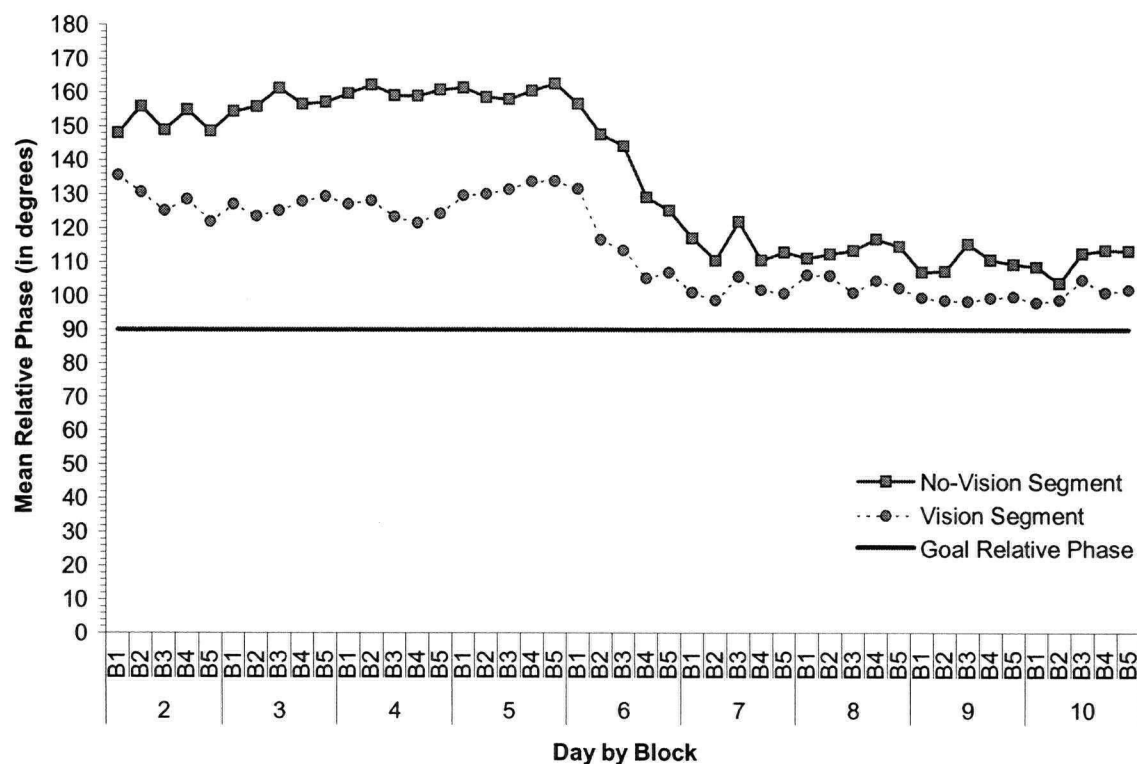


was sufficient for learning the criterion task².

In contrast, Figure 2.6 represents data from a participant who showed a strong attraction towards anti-phase. This bias proved difficult for the individual to break-away from. A plateau was observed in performance from Day 2 to Day 5, whereby the phasing relationship between the limbs was maintained at approximately 160° ($\underline{SD} = 9.9^\circ$) and 130° ($\underline{SD} = 8.8^\circ$) for the no-vision and vision segments, respectively. Although large gains were made on Day 6, performance was again observed to plateau. On the final 4 days of learning, performance was maintained at approximately 112° ($\underline{SD} = 11.1^\circ$) during the no-vision segment, while the vision segment was sustained at approximately 102° ($\underline{SD} = 8.9^\circ$). Although performance differences between the no-vision and vision segments decreased, the participant was never able to coordinate the limbs within a bandwidth of $\pm 10^\circ$ of the criterion pattern in the absence of feedback³. These data demonstrate the strong influence of anti-phase coordination when learning a new coordination task, especially when attempting to perform a criterion task in the absence of feedback. However, one question that arises for all 3 participants exhibiting the latter trend in performance is whether 3 s of visual feedback was sufficient to facilitate a break from preferred coordination tendencies. Given that participants executed approximately 1-1½ cycles in the vision segment, it may have been difficult to bring together enough information to optimize learning on subsequent attempts (For additional individual performance data see Figures 2.10 and 2.11 presented in Chapter Footnotes #4 and #5, respectively).

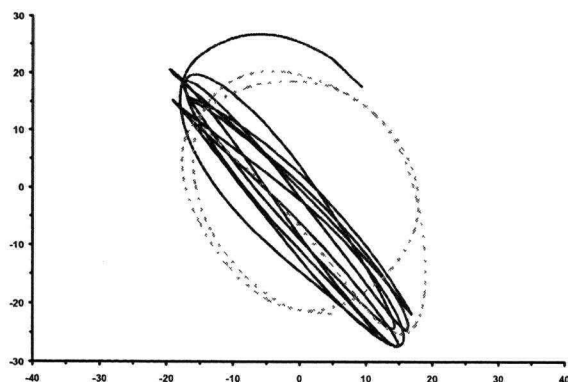
Cycle Frequency. When comparing cycle frequency, no significant main effect for segment emerged ($p = .151$). Mean cycle frequency for the no-vision segment was 0.706 Hz, while mean cycle frequency for the vision segment was 0.730 Hz. Individual data for mean cycle frequency is displayed in Table 2.1 for each segment collapsed across blocks.

Figure 2.6. Mean RP for Participant 3 plotted in blocks of 20 trials across nine days of acquisition for the no-vision segment and the vision segment (top panel). Performance is also presented in the form of Lissajous figures for select trials (bottom panel). The solid line represents the no-vision segment, the dotted represents the vision segment (x-axis = right forearm displacement; y-axis = left forearm displacement).



Day 3 Trial #250

No-Vision = 163° RP; Vision = 118° RP



Day 8 Trial #785

No-Vision = 108° RP; Vision = 104° RP

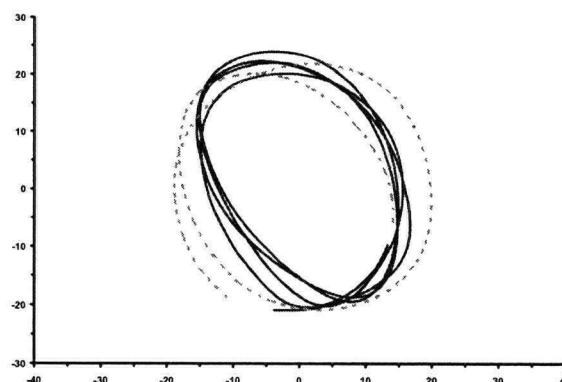


Table 2.1

Mean cycle frequency during the no-vision and vision segment for each participant collapsed across block.

		Day									
		1 ¹	2	3	4	5	6	7	8	9	10
Participant	V NV	V NV	V NV	V NV	V NV	V NV	V NV	V NV	V NV	V NV	V NV
1	0.4 0.6	0.4 0.4	0.5 0.5	0.5 0.4	0.7 0.7	0.7 0.7	0.6 0.6	0.8 0.7	0.6 0.6	0.6 0.6	0.6 0.6
2	1.0 0.9	1.4 1.4	1.1 1.2	1.2 1.2	1.2 1.2	1.2 1.2	1.2 1.2	1.1 1.2	1.2 1.2	1.1 1.1	1.1 1.2
3	0.3 0.7	0.8 0.8	0.7 0.8	0.7 0.8	0.7 0.7	0.6 0.6	0.6 0.6	0.5 0.5	0.6 0.6	0.6 0.6	0.5 0.6
4	0.8 0.8	0.8 0.7	0.7 0.7	0.8 0.7	0.7 0.7	0.7 0.7	0.7 0.7	0.7 0.6	0.6 0.6	0.6 0.6	0.7 0.6
5	0.4 0.6	0.3 0.5	0.3 0.3	0.3 0.4	0.3 0.4	0.4 0.4	0.4 0.4	0.4 0.4	0.4 0.5	0.4 0.5	0.4 0.4
6	0.8 0.8	0.6 0.7	0.6 0.6	0.7 0.8	0.8 0.9	0.9 0.9	0.9 0.9	0.8 0.9	1.0 1.0	0.9 0.9	0.8 0.8

¹ The shaded area represents data that were not included in the statistical analysis for reasons identified in Experiment 1.

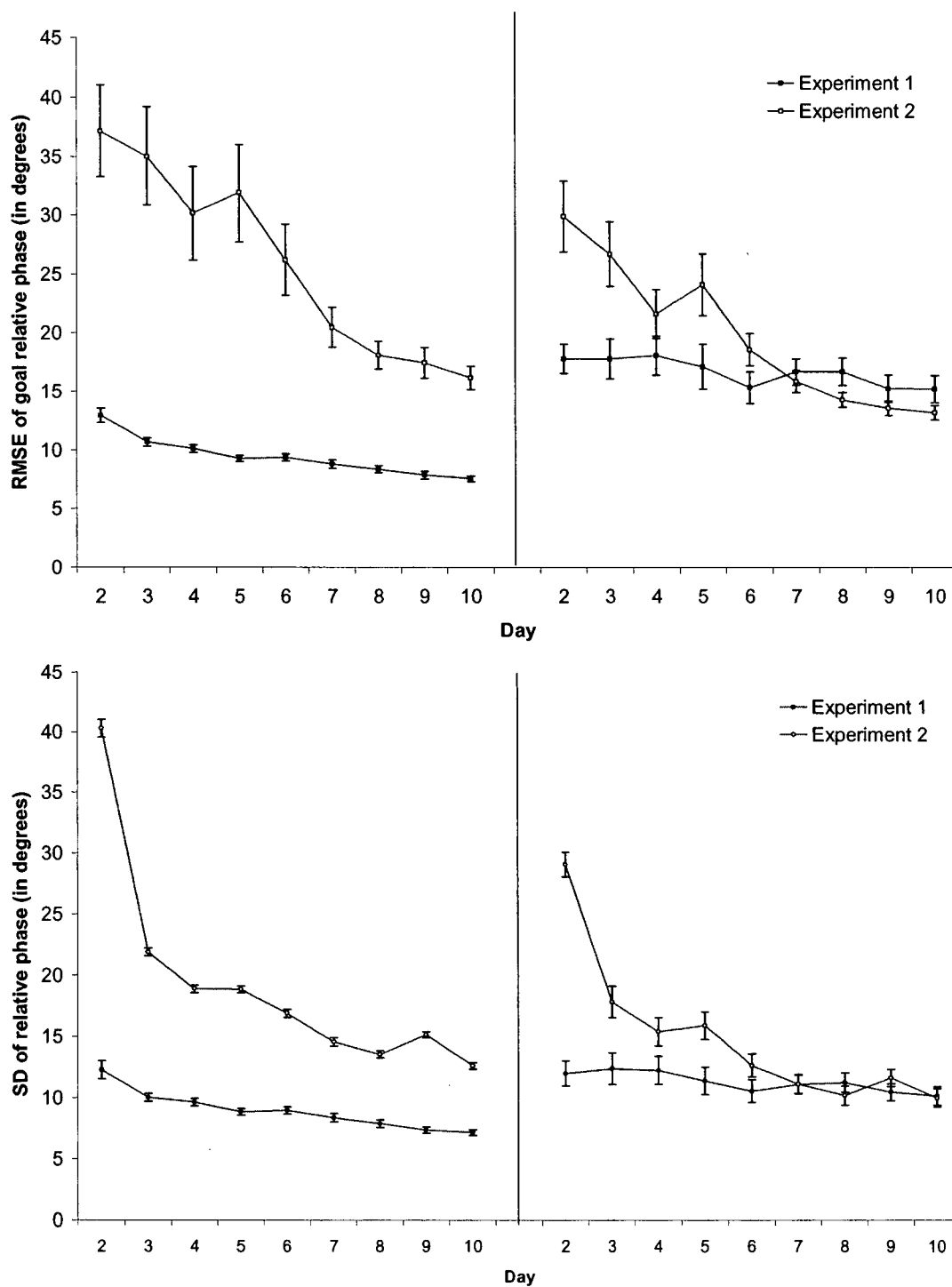
Pattern Accuracy and Stability across Experiments. Separate analyses were conducted for the 8.5 s segment and the 3 s segment, whereby the acquisition data of each dependent measure were compared to Experiment 1 using a $2 \times 9 \times 5$ (Group \times Day \times Block) ANOVA, with group as the between-subject factor. The group variable referred to Experiment 1 and Experiment 2.

Analysis of the 8.5 s segment showed that the group effect for both RMSE, $F(1, 10) = 7.03$, $p = .024$, and SD of RP, $F(1, 10) = 7.90$, $p = .018$, were significant. The 90° pattern was performed with greater accuracy and stability in the presence of concurrent on-line visual feedback (Experiment 1: \bar{M} RMSE = 9.5°; \bar{M} SD of RP = 9.0°), as compared to performance without relative motion feedback (Experiment 2: \bar{M} RMSE = 25.9°; \bar{M} SD of RP = 19.2°). Analysis also revealed a significant group by day interaction for accuracy (RMSE, $F(8, 80) = 2.95$, $p = .006$), as well as stability (SD of RP, $F(8, 80) = 2.24$, $p = .033$). By Day 2, participants in Experiment 1 already exhibited superior performance in comparison to the participants' performance in Experiment 2. As such, the performance gains observed in Experiment 1 were smaller than the improvements observed for participants in Experiment 2 across days.

A significant interaction effect for group by day was also demonstrated when analyzing the 3 s segment for RMSE, $F(8, 80) = 3.38$, $p = .002$, and SD of RP, $F(8, 80) = 2.32$, $p = .027$. Greater changes in performance were demonstrated across practice for participants in Experiment 2, in comparison to gains observed in Experiment 1. There was no significant main group effect for RMSE ($p = .523$) or SD of RP ($p = .336$).

Figure 2.7 represents RMSE of goal relative phase (top panel) and SD of RP (bottom panel) plotted separately for each trial segment (left panel = 8.5 s segment; right panel = 3 s segment) and compared across experiments. With respect to the present investigation, visual inspection of the graph shows that performance during the 8.5 s segment continued to improve across practice and eventually reached comparable levels with no-vision (3 s) performance in Experiment 1. Pattern accuracy and stability also improved with practice during the 3 s segment in Experiment 2. However, performance never reached the level displayed in the 8.5 s

Figure 2.7. RMSE of goal relative phase (top panel) and SD of RP (bottom panel) plotted separately for each trial segment and compared across experiments. The left panel represents the 8.5 s segment and the right panel represents the 3 s segment (Error bars = SEM).



segment in Experiment 1, even though participants in the present investigation received relative motion feedback for this portion of the trial.

Performance of the 90° pattern generally improves in the presence of concurrent visual feedback. In the present investigation, wide ranges of performance were observed for the 90° out-of-phase task. For some individuals, performance was similar irrespective of whether continuous visual feedback was or was not available to guide performance. For other learners, large differences in performance were displayed between segments for the duration of the experiment. That is, performance of the 90° pattern was superior when on-line relative motion feedback was available to guide performance in comparison to conditions without visual feedback. However, even in the vision segment, these participants were often unable to readily overcome the influence of intrinsic coordination tendencies to produce the required pattern.

As a result of the limited availability of visual feedback, performance in the vision (3 s) segment of the present investigation did not reach the level of performance displayed in the vision (8.5 s) segment of Experiment 1. In lieu of specific instructions regarding how to produce the to-be-learned pattern, these data demonstrate the important role of concurrent visual feedback for inhibiting the attraction of intrinsic coordination tendencies and for getting an idea of the required coordination pattern.

Question 3: Did a Performance Advantage Emerge in No-feedback Transfer Tests for Learners Receiving Limited Relative Motion Feedback during Acquisition?

No-feedback transfer tests were analyzed separately for RMSE and SD of RP using a Group (Experiment 1, Experiment 2) x Day (8) x Segment (8.5 s segment, 3 s segment) x Block (4) mixed design ANOVA, with group as the between-subject factor. Results revealed no significant difference between Experiments 1 and 2 for RMSE ($p = .868$) or SD of RP ($p = .408$). However, accuracy and stability of the 90° pattern improved across practice, as evidenced by a significant main effect for day

(RMSE, $F(7, 70) = 6.67$, $p = .0000$; SD of RP, $F(7, 70) = 6.14$, $p = .0000$). A performance advantage did not emerge in no-feedback transfer tests for learners receiving reduced continuous visual feedback to guide performance. Figure 2.8 illustrates RMSE of goal relative phase (top panel) and SD of RP (bottom panel) for Experiments 1 and 2.

Question 4: Did Extended Practice on a Bimanual Coordination Task Reduce and Eventually Eliminate Dual-Task Interference?

Probe-RT during Acquisition. The probe data were subjected to a Day (9) x Segment (2) x Task Condition (probe-RT, baseline RT) x Probe position (4) ANOVA, with repeated measures on all factors (following preliminary analysis of the data⁶). Mean RT for the secondary task baseline condition was calculated from both pre- and post-acquisition measures ($M = 423$ ms; $SD = 72$ ms) and used for all cells of the baseline condition in the ANOVA. Baseline RT was computed from both measures because a one-way repeated measures ANOVA revealed no significant difference ($p = .536$) between pre-acquisition ($M = 412$ ms; $SD = 70$ ms) and post-acquisition ($M = 434$ ms; $SD = 73$ ms) RT.

Analysis revealed a significant two-way interaction for day x task condition, $F(8, 40) = 7.19$, $p = .000$, and segment x task condition, $F(1, 5) = 12.98$, $p = .016$. Figure 2.9 (top panel) presents mean probe-RT for each segment across days compared to baseline RT. Findings revealed that probe-RT was significantly faster when responding to the auditory probe alone than when responding while performing the 90° out-of-phase task. Although mean probe-RT decreased from 666 ms ($SD = 97$ ms) on Day 2 to 557 ms ($SD = 103$ ms) on Day 10, it did not reach baseline levels. Post-hoc analysis of the segment by condition interaction also showed that probe-RT was significantly faster in the no-vision (8.5 s) segment versus probe-RT in the vision (3 s) segment of the trial. Mean probe-RT for both segments were significantly different than baseline RT on all days of acquisition. No significant main effect was found for probe position ($p = .849$).

Figure 2.8. RMSE of goal relative phase (top panel) and SD of RP (bottom panel) for immediate and delayed no-feedback transfer tests across days, Experiment 1 vs. Experiment 2 (Error bars = SEM).

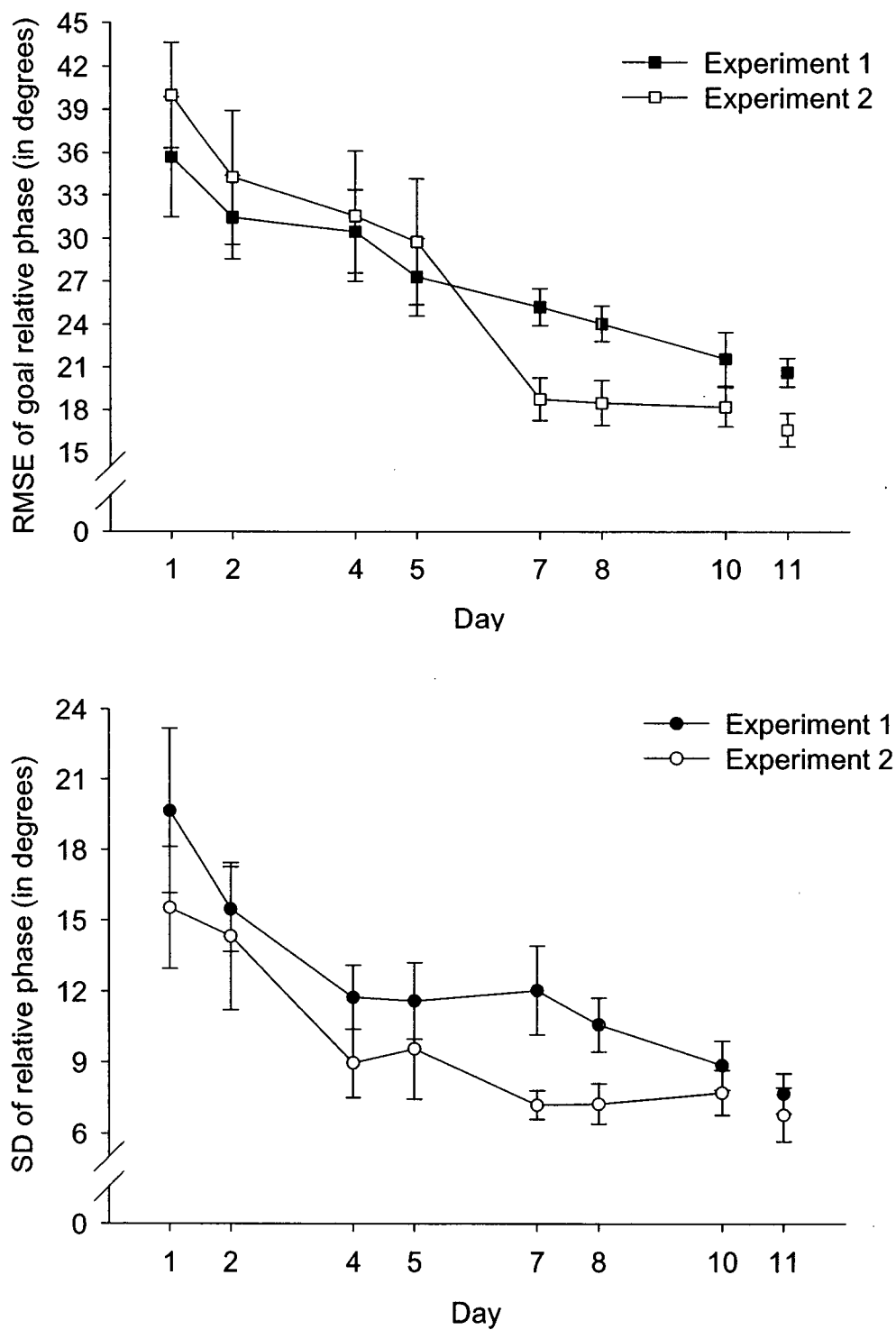
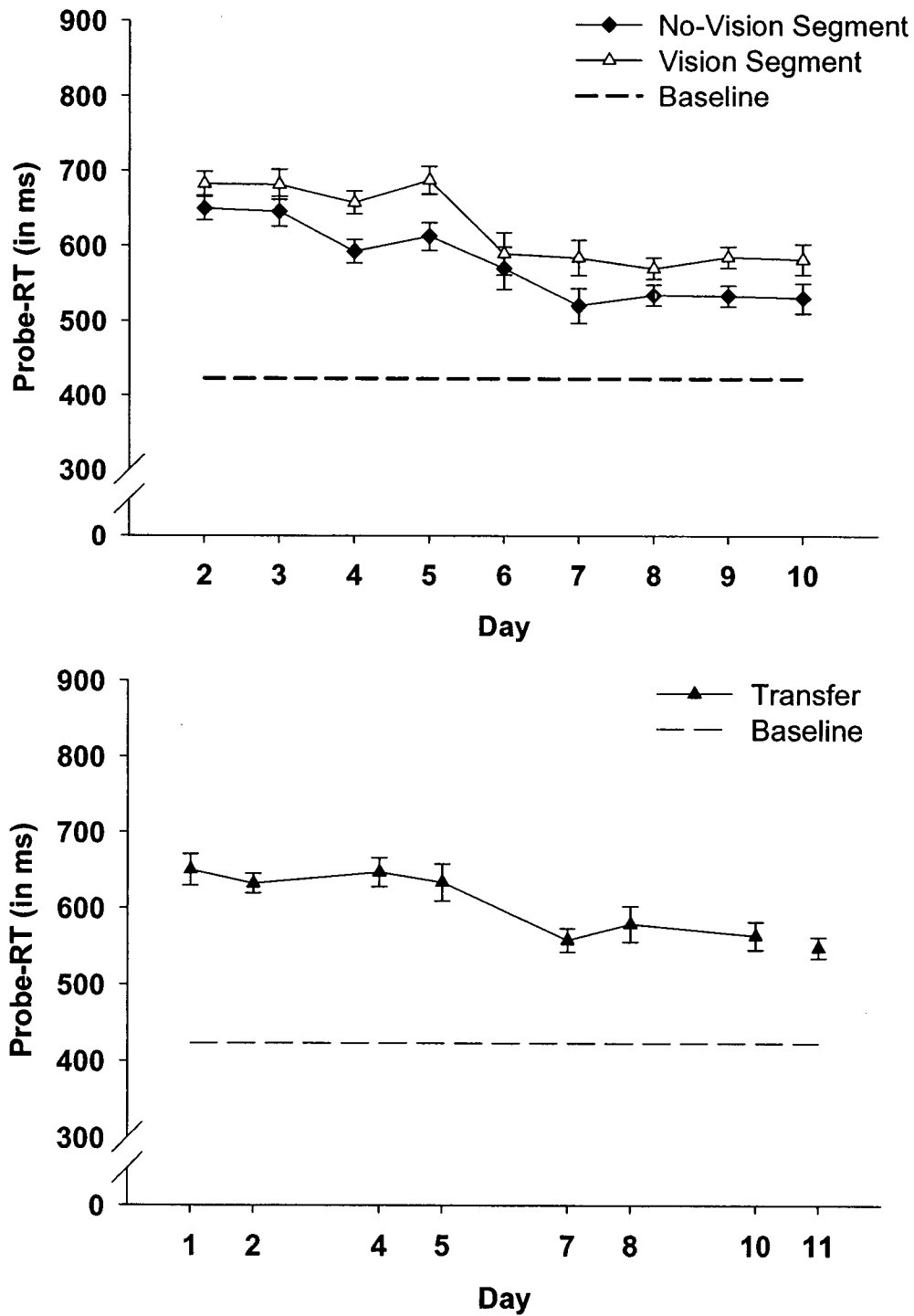


Figure 2.9. Mean probe-RT for acquisition (top panel) and transfer (bottom panel) plotted as a function of day and compared to baseline RT ($M = 423$ ms) (Error bars = SEM).



Probe-RT during Transfer. The data were submitted to a Condition (transfer probe-RT, baseline RT) x Day (8) x Probe (4) ANOVA, with repeated measures on all factors. Findings revealed a significant interaction effect for condition x day, $F(7, 35) = 3.54$, $p = .006$. Post-hoc analysis revealed that mean probe-RT was significantly slower than baseline measures on each day of transfer, although it improved from Day 1 through to Days 10 and 11 ($M = 650, 564$, and 549 ms, respectively). Figure 2.9 (bottom panel) displays mean probe-RT under transfer conditions compared to baseline RT. There was no main effect for probe position ($p = .080$).

Dual-task interference was reduced, but not eliminated following extended practice of the 90° pattern. Probe-RT measures collected during both acquisition and transfer trials revealed that performance of the 90° pattern continued to demand attention after ten days of task-specific practice, and following a one-week retention interval of no practice. Therefore, dual-task interference was not eliminated under practice conditions of reduced visual feedback and explicit instructions. Results also showed that attention demands were greatest when performing the task in the presence of concurrent visual feedback in comparison to attention requirements in the absence of relative motion feedback.

Discussion

Previous research has demonstrated the effectiveness of providing continuous on-line feedback for the learning of a new bimanual coordination task (e.g., Lee et al., 1995). Due to its usefulness, one issue that has emerged is whether individuals become increasingly dependent on this type of information as learning progresses. The purpose of the present investigation was to examine the effects of reducing the availability of continuous relative motion feedback for the learning of a 90° out-of-phase task. This was manipulated by reducing the amount of feedback from 8.5 s, as provided in the beginning of the trial in Experiment 1, to the final 3 s of the trial. Decreasing availability of continuous visual feedback should encourage the processing of sensory information sources intrinsic to the task,

thereby facilitating performance when feedback is unavailable to guide coordinative movements.

Overall, results showed that participants exhibited a slower rate of acquisition when compared to the results of Experiment 1. A large difference in performance was already evident by the second day of practice, whereby performance in Experiment 1 was superior during the 8.5 s segment, irrespective of whether the 90° pattern was performed in the presence or absence of relative motion feedback in the present experiment. A substantial gain in performance suggests that participants in the Experiment 1 acquired a rudimentary idea of the movement much earlier in the learning process, which is attributed to the greater availability of concurrent visual feedback. Subsequently, smaller gains in performance were evidenced from Days 2 to 10, which indicates that the learners were now more focused on refining the coordination pattern (e.g., increasing the consistency of each relative motion trace superimposed onto the criterion template).

When examining individual data, results showed that getting an idea of the movement proved especially difficult for several of our participants under reduced conditions of visual feedback. Due to the self-regulatory nature of the learning environment, the performer required the information provided by real-time relative motion feedback, as well as terminal feedback, to formulate a rudimentary representation of the required task. In lieu of specific instructions addressing how to achieve the required pattern, visual feedback was essential for specifying how the system can be controlled. Therefore, an obvious contributing factor to the difficulties observed, was the self-selected cycle frequency of learners. With only one exception, all participants consistently moved at a frequency of less than 1 Hz. This is especially problematic because real-time relative motion feedback was only provided for 3 s, and in that time frame participants only completed 1-1 ½ movement cycles (on average). It is possible that individuals were not provided enough time to effectively utilize the relative motion feedback and learn the nature of the phasing relationship between the limbs. This ultimately influenced rate of acquisition, as well as the quality of the new coordination pattern. Given the importance of the 3 s segment, it is interesting that participants did not increase their rate of cycle

frequency in an attempt to obtain more exposure to the concurrent visual feedback. Instead, they maintained their preferred rate of frequency in both segments of the trial, as well as across practice.

The negative effects of removing concurrent relative motion feedback for learning a new bimanual coordination pattern have been documented elsewhere in the literature. For example, Wishart, Lee, Cunningham, and Murdoch (2002) have reported that older adults were unable to learn the 90° out-of-phase task when feedback was reduced to terminal relative motion plots after every fifth trial. These findings emerged despite the fact that the older adults could verbally describe the requirements of the task (i.e., one limb leads the other by a $\frac{1}{4}$ of a movement cycle) and a group of younger counterparts were successfully able to learn the task. Wishart et al. hypothesized that older individuals, in comparison to young, have more difficulty breaking away from, or inhibiting the influence of, pre-existing coordination tendencies. These predictions were based on the finding that the average pattern performed by the older adults was either a 20° pattern (i.e., a strong bias towards in-phase) or a 160° pattern (i.e., a strong bias towards anti-phase). Moreover, participants did not show improvements on any performance measure, even after three days of practice.

Based on our findings, we would suggest that problems breaking away from the influence of pre-existing coordination tendencies also occurred for some of our participants. For example, after 3 days of practice, one participant continued to perform a 160° RP pattern, while another participant coordinated the limbs in a 140° RP pattern. In our study, we provided more feedback (i.e., a relative motion plot after every trial vs. every fifth trial; and concurrent visual feedback for 3 s of every trial vs. no concurrent feedback); yet, these participants continued to exhibit a strong coordination preference towards anti-phase. Therefore, sensitivity to the availability of continuous relative motion feedback may not be strictly age-related.

An important question in the present investigation was to examine whether specificity of learning effects would emerge for continuous on-line visual feedback when learning a new bimanual coordination pattern. In recent years, Swinnen et al. (1997) were unable to provide evidence in support of the specificity of learning

hypothesis. They compared the performance of three groups on the acquisition of a 90° out-of-phase task. In addition to terminal feedback following every fifth trial (in the form of a Lissajous figure), one group received relative motion feedback during performance of the 90° pattern (enhanced vision), while a second group was only permitted normal vision of the limbs (normal vision). Finally, a third group was required to perform the pattern blindfolded (reduced vision). Transfer tests were administered under enhanced vision, normal vision, and blindfolded criterion test conditions. Findings revealed that the real-time feedback group was not only more successful at the 90° out-of-phase task in acquisition, but also outperformed the other two groups under all criterion conditions. Swinnen et al. concluded that the enhanced vision group learned an action plan that generalized to various conditions. Therefore, concurrent relative motion information has beneficial effects for learning and does not make a learner vulnerable when it is no longer available to guide performance.

In contrast to Swinnen et al. (1997), our findings provide some support for the specificity of learning hypothesis. When comparing the no-feedback transfer tests, analysis revealed no significant differences in pattern accuracy and stability between Experiments 1 and 2. The superior acquisition performance demonstrated by participants during the 8.5 s segment in Experiment 1 did not emerge when relative motion feedback was removed in transfer tests as Swinnen et al. have shown. Moreover, some interesting trends were also revealed between Experiments 1 and 2. Early in learning, participants in Experiment 1 generally performed the 90° pattern with less error in comparison to participants in Experiment 2. However, on the last four transfer tests, findings showed that the 90° pattern was performed with less error in Experiment 2, even after a one-week retention interval of no practice. This reversal effect is most likely a result of the large gains in performance that several participants made following the fifth day of practice in the present investigation. Thus, the benefits gained from performing the 90° pattern in the presence of concurrent visual feedback does not necessarily generalize to various performance contexts. Rather, reducing availability of relative motion feedback may have some

benefits for performance when the conditions of practice are similar to the conditions of transfer.

These results also show that voluntary stabilization of the criterion bimanual coordination task incurred an attentional cost, as measured by probe-RT, even after extended periods of task-specific practice. Given the difficulty of learning the new bimanual task under conditions of reduced feedback, performance gains were generally displayed throughout the time course of practice. In fact, for some participants, large gains were not exhibited until later stages of the experiment (i.e., after 500 practice trials). Whenever learning takes place and motor performance continues to improve, interference between a primary and a secondary task is predicted to persist (Blischke, 1998). The findings also suggest that the provision of relative motion feedback incurred a greater attentional cost in comparison to the central costs associated with performing the 90° pattern in the absence of real-time feedback. These results are contrary to Experiment 1, whereby attention demands were greatest when relative motion feedback was unavailable to guide performance. This indicates that attentional demands increase when the learner is required to switch between feedback sources within a trial (e.g., from visual sources to proprioceptive sources, or vice-versa). However, when considering that the final segment of the trial was only 3 s in both experiments, it remains unclear whether this central cost is a temporary effect, or more permanent in nature. It is possible that adding or removing augmented feedback within a trial induces a momentary increase in attention demands. Once the individual adjusts to the new information source, central costs may subsequently decrease. The attention demands of visual and proprioceptive feedback sources are discussed in more detail in Experiment 5 of this thesis.

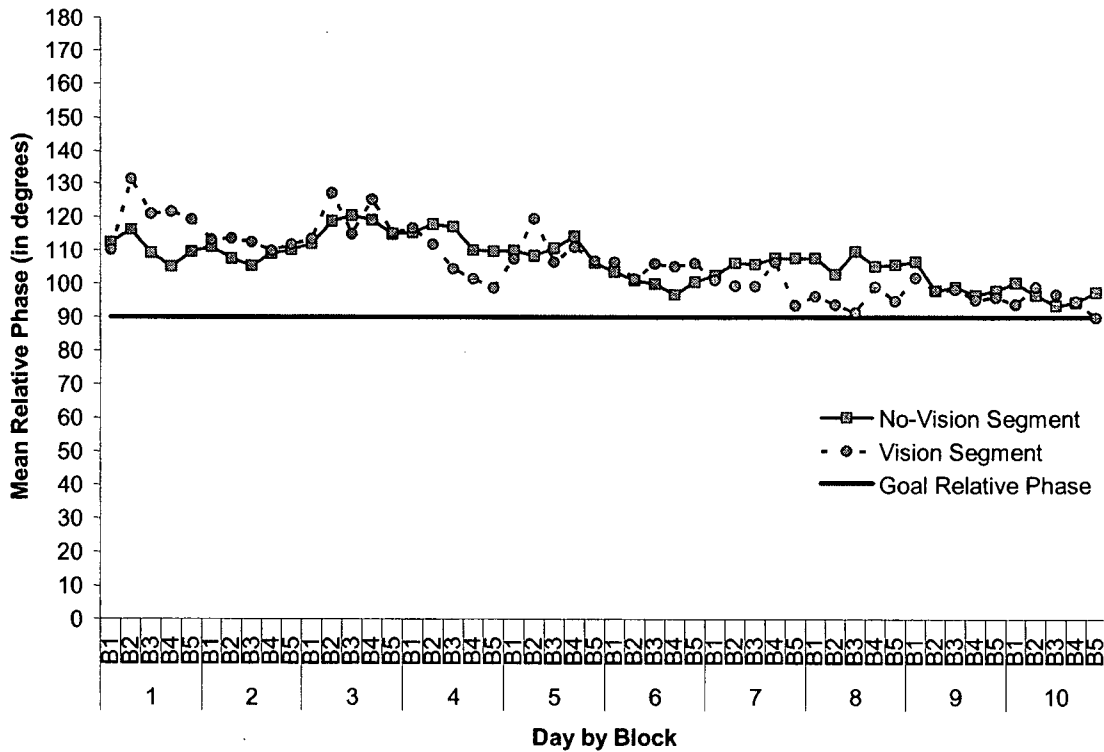
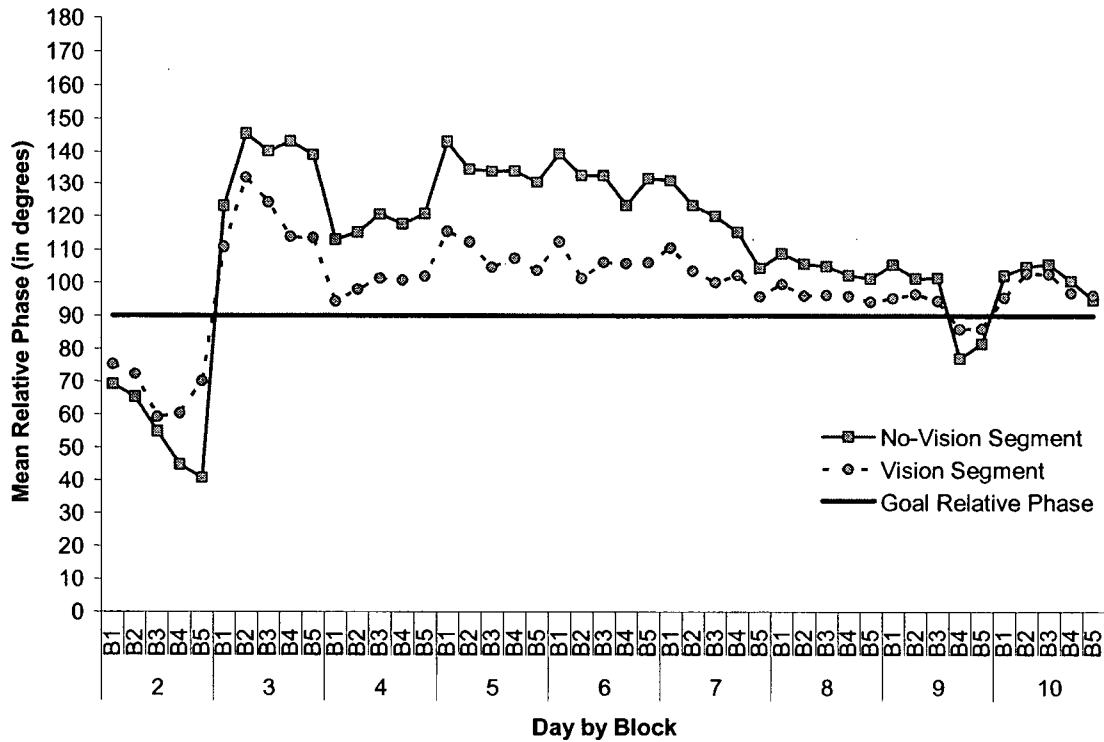
Chapter Footnotes

- 1 The no-vision segment in Experiment 1 was initially designed to only be 3 s in duration because we were mainly interested to see whether the individual could maintain the criterion pattern when visual feedback was removed. With practice, we predicted that individuals would be able to maintain the 90° pattern. Contrary to our prediction, several individuals displayed coordination preferences towards anti-phase in the absence of relative motion feedback, even after 1, 000 practice trials. One possible explanation for this finding suggests that removing augmented feedback may act as a perturbation, inducing a temporary disruption in coordination performance. Given that the last segment of the trial was only 3 s, and participants performed at an average frequency of 0.6 Hz, it is possible that we did not provide the performer an adequate opportunity to recover from a possible perturbation. However, for purposes of analysis we maintained the time duration of each segment for Experiments 2 and 3, and further addressed this design limitation in Experiment 5 of this thesis.

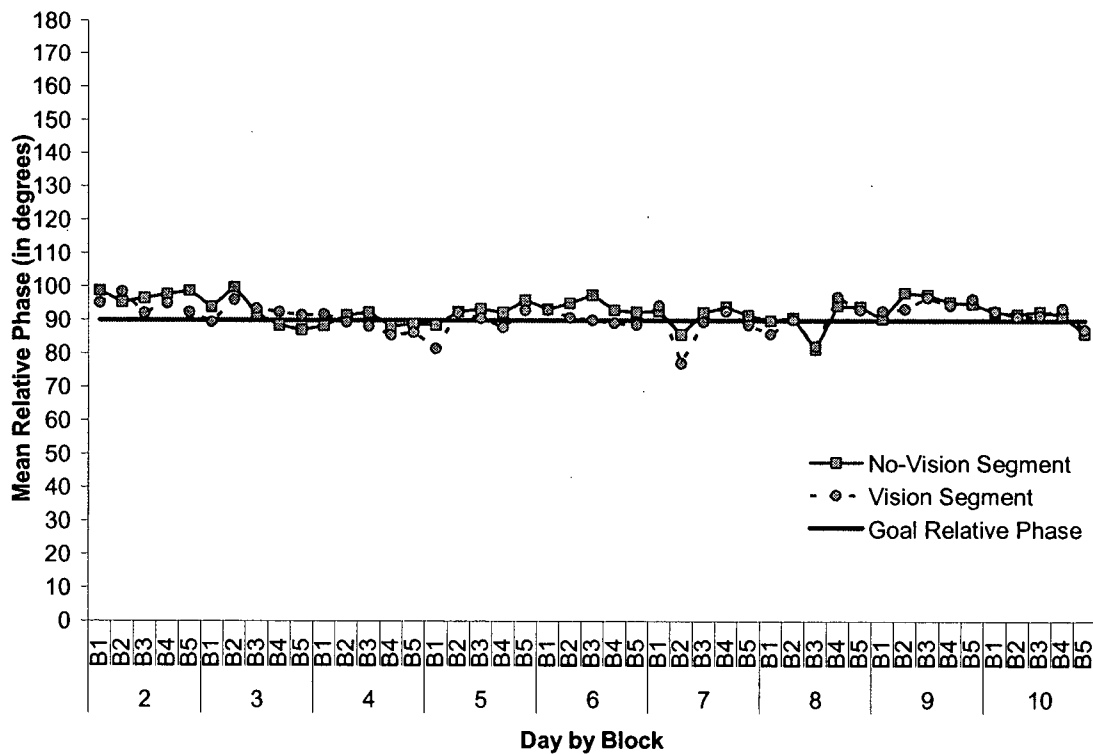
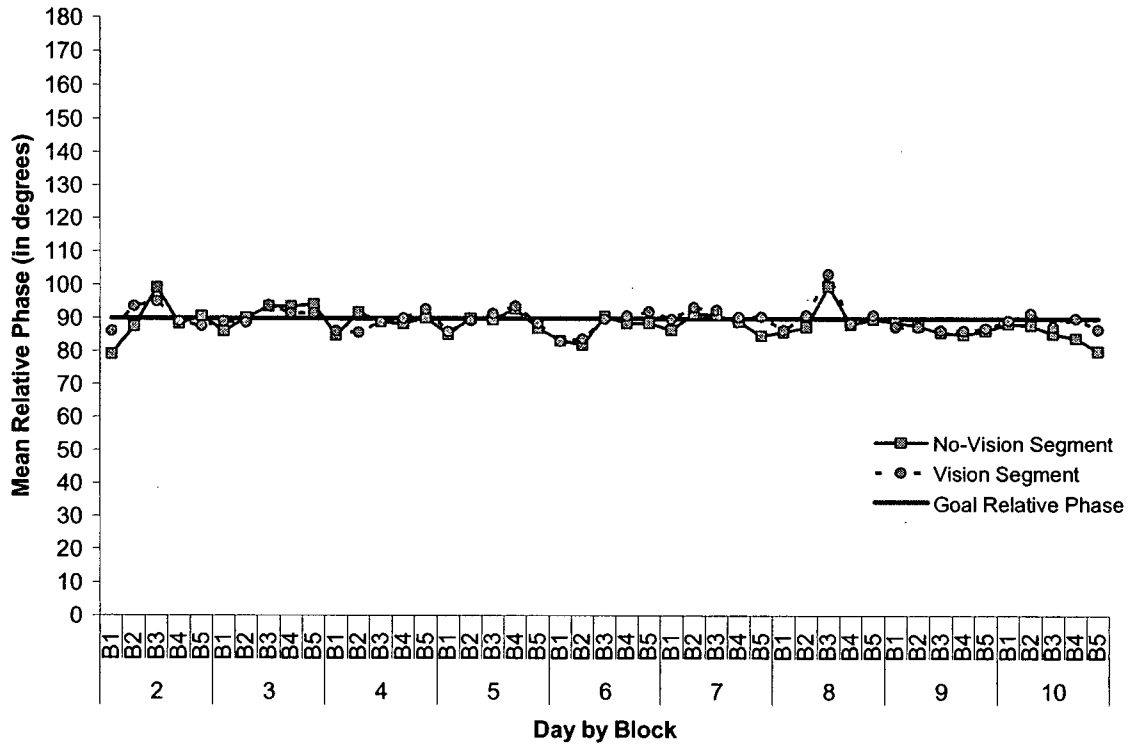
For Footnotes #1 and #2, refer to Appendix B – Using the Scanning Procedure for Mapping Dynamical Landscapes: Methodological Implications.

- 2 The ease at which Participant 4 acquired the 90° pattern may be explained by discussing the data collected for pre-acquisition scans of the coordination dynamics. The pre-scan data revealed a preferred tendency towards 0°, 90°, and 180° RP. This suggests that the individual may have already possessed a multi-stable regime prior to practice (see Appendix B, Figures B4-B5).
- 3 Post-scans revealed no development of an attractor at the 90° pattern (see Appendix B, Figures B6-B7).

- 4 **Figure 2.10.** Mean RP for Participant 2 (top panel) and Participant 5 (bottom panel) plotted in blocks of 20 trials across 9 days of acquisition for the no-vision segment and the vision segment. Performance within a bandwidth of ± 10 of the criterion pattern did not occur until late stages of learning.



- 5 **Figure 2.11.** Mean RP for Participant 1 (top panel) and Participant 6 (bottom panel) plotted in blocks of 20 trials across 9 days of acquisition for the no-vision segment and the vision segment. Relatively accurate performance of the 90° pattern emerged early in learning.



- 6 As previously discussed in Experiment 1, a preliminary analysis was conducted to verify that performance of the 90° pattern was maintained on trials where a probe occurred, in comparison to no-probe trials. RMSE was calculated and submitted to a Trial Type (no-probe, probe) x Day (9) repeated measures ANOVA. Findings revealed no significant difference for trial type ($p = .113$). Mean RMSE was 24.8° and 25.6° for the no-probe and probe trials, respectively. We also conducted a second analysis to verify that performance of the 90° pattern was the same 1 cycle before and 1 cycle after the probe. Mean RMSE data was submitted to a Time (pre-probe, post-probe) x Day (9) repeated measures ANOVA for the no-vision segment only. Results also showed no significant difference ($p = .192$) in RMSE prior to ($M = 25.0^\circ$) and following an auditory probe ($M = 27.3^\circ$). Taken together, these findings indicate that participants did not share attentional priority with the secondary task, but maintained attentional focus on the 90° out-of-phase task.

CHAPTER III

EXPERIMENT 3

Effects of Manual Guidance on Attention Demands and Extended Learning of a New Bimanual Coordination Task

Introduction

In the applied setting, it is common to employ instructional techniques that provide a guiding function. These might include the use of verbal cues or knowledge of results (KR), as well as physical or manual guidance. The rationale behind use of any guidance technique is that it helps learners gain a better idea of the criterion movement, helps reduce the number of errors that the learner makes, and provides more security for the individual in learning environments that are potentially dangerous by the very nature of the tasks performed (e.g., gymnastics, weightlifting) (Schmidt & Lee, 1999; Tsutsui & Imanaka, 2003; Wulf, Shea, & Whitacre, 1998). Based on these ideas, instructors generally assume that guidance facilitates the acquisition of a new motor skill. In the present investigation, the effectiveness of manual guidance on acquiring a new bimanual coordination task was examined.

Manual Guidance

Manual guidance is described as a procedure used to help learners experience sensory information that is derived from correct movements of the goal task (Tsutsui & Imanaka, 2003). For example, an instructor can provide manual guidance by moving the learner's passive limb(s) through the desired movement. Although practitioners often advocate the use of manual guidance in the instructional setting, research investigating the effects of manual guidance on motor skill learning has been sparse. Moreover, the results of investigations that have examined the effectiveness of manual guidance techniques have generally shown that guidance provides only temporary effects on motor performance (e.g., Armstrong, 1970; Hagman, 1983; Winstein, Pohl, & Lewthwaite, 1994).

Reasons provided for the ineffectiveness of manual guidance generally relate to the fact that the limb is passive when it is moved through the criterion task (Schmidt & Lee, 1999). Performance benefits are limited because the learner receives different sensory motor information than what would be received if the person was actively performing the task. Importantly, when experiencing a correct movement in a passive way, the individual is unable to obtain critical error information about the task or generate his or her solutions to the movement problem by way of discovery or trial and error learning.

Of the few experiments that have examined manual guidance, simple tasks have generally been employed, which involve relatively few degrees of freedom. For example, Armstrong (1970) asked participants to move a lever in a specified spatial-temporal pattern, while Hagman (1983) and Winstein et al. (1994) required individuals to perform positioning movements to a mechanical stop. More recently, Wulf, Shea and Whitacre (1998) have advocated an approach that examines guidance using coordination tasks involving large numbers of degrees of freedom.

Examining the effects of physical guidance on the learning of a complex ski-simulation task, Wulf et al. provided support for the use of physical guidance for learning complex coordination tasks. When learners were provided a pair of ski poles to use as a guidance tool, they were able to produce a pattern that they would not have otherwise been able to perform until more advanced stages in learning. Most importantly, efficiency of the movement pattern was maintained when the ski poles were removed in immediate and delayed retention tests. Wulf et al. concluded that the ski poles were advantageous to the learning process because it provided the learner with an idea about how the goal movement pattern should feel. In addition, the learner actively produced the required movement. Used in this manner, guidance tools may be highly effective for motor skill learning.

In a more recent investigation, Tsutsui and Imanaka (2003) examined the effectiveness of manual guidance for learning a 90° out-of-phase pattern. Findings showed that participants receiving manual guidance only, did improve their performance, although this method was less effective than just physical practice. Interestingly, no performance advantage emerged for participants receiving both

manual guidance and physical practice. As such, Tsutsui and Imanaka concluded that the learning benefits of manual guidance were limited for several reasons. In their study, participants were passively guided through the bimanual coordination pattern by an expert performer. Once again, the learner was not engaged in active practice of the movement, nor did (s)he experience movement errors. For guidance to be effective in the learning of a bimanual coordination task, Tsutsui and Imanaka postulated that the learner needs to be engaged in the problem-solving experiences that arise from actively executing the movement.

Overview of Experiment

The most difficult component of learning a new bimanual coordination task is realizing how to break away from pre-practice behaviours, as well as resisting the influence of intrinsic patterns when task conditions change. For the practitioner or motor learning theorist, determining practice variables that will decrease the effects of pre-practice behaviours is important for the instructional setting. In Experiment 1, we found that participants were highly successful at producing a 90° out-of-phase pattern when concurrent visual feedback was provided to guide performance; however, they were less adept at modifying the influence of pre-practice behaviours when visual feedback was removed. Because participants received real-time relative-motion feedback for 65% of each and every trial, we concluded that participants became over-reliant on the visual feedback and were unable to process critical proprioceptive features of the task. As a consequence, these individuals performed poorly when visual feedback was no longer available to guide the coordination movement. To further examine the influence of continuous on-line visual feedback on learning a new coordination pattern, we conducted an additional experiment where availability of visual feedback was restricted to a total of 4.5 s (or 35%) of each trial. The purpose of reducing availability of relative motion feedback was to encourage attention to critical sources intrinsic to the task, thereby facilitating performance of a 90° out-of-phase pattern when visual feedback is unavailable. Results showed that reduced availability of on-line visual feedback had a critical impact on rate of acquisition and several of our participants experienced great

difficulty overcoming pre-existing behavioural tendencies to acquire the criterion pattern. Due to the self-regulatory nature of the learning environment, we suggested that learning was hindered in the early stages of acquisition because participants experienced difficulty formulating a general understanding or rudimentary representation of the required task. Therefore, the purpose of the present investigation was to examine the manual guidance technique for learning the 90° out-of-phase pattern.

Participants engaged in 10 sessions of 100 practice trials across a two-week period (i.e., 1,000 trials). Each trial was broken up into three segments as previously described in Experiment 2. Continuous on-line feedback was provided for only initial calibration to the computer monitor (1.5 s) and the final (3 s) segment of the trial. Participants received no feedback for the middle (8.5 s) segment. Following each trial, terminal feedback of the just-performed no-vision segment was provided. Unlike Experiment 2, however, participants also received manual guidance. This was accomplished via a set of servo torque motors attached to the manipulanda. Immediately following provision of terminal feedback, the servo motors became operational and moved the participant's limbs for a period of 12 s, which was subdivided into two time intervals. For the first 6 seconds, participants received a summary playback of their own limb movements from the just-performed trial. The motors then moved the participants' limbs in the required phase offset for the final 6 s. This manipulation provided the learners an opportunity to identify their own movement errors by comparing their performance against the goal movement. We postulated that moving the participant's limbs in the required pattern would help the learner get a general idea of the goal movement, as well as experience with error information, thereby facilitating rate of acquisition and quality of the required coordination pattern. Identical to Experiments 1 and 2, we also assessed the attentional costs of performing a 90° out-of-phase task. We postulated that performance would continue to improve across practice (as previously demonstrated in our previous two investigations); therefore, attention demands of the 90° pattern were predicted to decrease as a function of practice, but elimination of dual-task interference was not expected to emerge.

Method

All methods were identical to the previous experiments with the following exceptions.

Participants

Informed consent was received from six self-professed right-handed individuals from a university population ($n = 5$ females; $n = 1$ male). The mean age of participants was 22.7 years ($SD = 3.7$, range = 19-29 years). All individuals were naïve to the purpose of the experiment and none had previous experience as a participant in a bimanual coordination investigation. Upon completion of the final session, all participants received remuneration. The experiment was carried out according to the ethical guidelines set by the University Behavioural Science Screening Committee for research involving human participants.

Apparatus

As previously described, participants were seated at a table facing a colour monitor with their forearms strapped comfortably into two angular manipulanda. In the present experiment, however, each manipulandum was connected to a servo torque motor (Mavilor MT-600) controlled via a motion control card (Tech-80 model 5638) and servo amplifier (Infranor SMVEN 2410). Angular positions of the manipulanda were recorded using two optical encoders (Dynapar, E2025001303), one mounted on each servo motor. Both optical encoders were attached to an interface card (Advantech Quadrature, PCI-833) giving 10, 000 counts per revolution, or a resolution of 0.036 degrees.

Procedure

During acquisition, participants received the same schedule of visual feedback as described in Experiment 2. Visual feedback was provided for the first 1.5 s of each trial, whereupon vision was removed and participants received no relative motion feedback for the next 8.5 s. At the 10 s mark, visual feedback was restored and remained on the screen for the final 3 s of the trial. At the completion of

each trial, participants received terminal feedback of the just-performed no-vision segment (8.5 s) trial segment, which was superimposed over the criterion template and the orthogonal plot produced during the vision (3 s) segment of the trial. Each segment was plotted in different colours in the form of a Lissajous figure.

During each 13 s trial, the participant solely drove movements of the limbs. The servo torque motors were inoperative, acting only as small passive inertial and frictional loads on each manipulandum during participant-driven movement. However, immediately following the provision of terminal feedback, the servo motors became operational, physically moving the participant's limbs for 12 s. This 12 s time interval was divided into two segments. First, participants' received a playback of their own limb movements from the just-performed trial. The last 3 cycles of recorded movement in the no-vision segment was selected by the computer running customized software. The average cycle speed for the participant's movement was calculated, then speeded or slowed to play back at 0.5 Hz for 6 s. Following playback of the participant's movements, the servo torque motors then moved the right and left limbs at the required phase offset of 90°. Playback of the criteria movement consisted of three cycles of movement at 0.5 Hz over the final 6 s of the time interval. Following explanation of the 12 s playback component of the experiment, participants were reminded that they did not have to move the limbs at the speed of the servo torque motors (i.e., 0.5 Hz); rather they could move at their own self-selected frequency.

All procedures for immediate and delayed transfer tests were identical to Experiments 1 and 2. The servo torque motors were inoperative during all transfer phases. No external instructions were provided to the learner at any time during the experiment.

Results

In the same manner as Experiment 2, the results are presented according to four main questions. These are: (1) Did performance of the required pattern improve with practice? (2) Did performance differences appear between segments? (3) Did a performance advantage emerge in no-feedback transfer tests when compared to

Experiments 1? and finally, (4) Did extended practice on a bimanual coordination task reduce and eventually eliminate dual-task interference?

Question 1: Did Performance of the Required Pattern Improve with Practice?

Changes in Pattern Accuracy and Stability across Acquisition. The dependent measures of RMSE and SD of RP were submitted to a $9 \times 2 \times 5$ (Day \times Segment \times Block) ANOVA, with repeated measures on all factors. As previously discussed, Day 1 was not included in the analysis because several participants did not complete one full movement cycle within the initial blocks of trials.

Practice improved performance towards the criterion pattern (i.e., 90° RP) as confirmed by a main effect for day, $F(8, 10) = 4.34$, $p = .0008$. The evolution of task performance is illustrated in Figure 3.1 across days for RMSE (top panel). When compared to Day 2, RMSE improved by 9% and 12% on Days 3 and 4, respectively. A gradual rate of improvement continued through Day 5 (17%) and Day 6 (16%), followed by a maximal gain of 29% on Day 7. On the final three days of acquisition performance was 23% (Day 8), 26% (Day 9), and 27% (Day 10) more accurate as compared to Day 2. Percent improvement scores are illustrated in Figure 3.2 for RMSE. Analysis also revealed a significant main effect for block, $F(4, 20) = 8.05$, $p = .004$. Blocks 3, 4, and 5 ($\bar{M} = 15.5^\circ$, 15.3° , and 14.6° ; $SD = 5.4^\circ$, 4.9° , and 4.2° , respectively), were performed with significantly less error as compared to Block 1 ($\bar{M} = 17.2^\circ$, $SD = 5.7^\circ$).

The 90° relative phase task became more stable with increasing practice, as evidenced by a main effect for Day, $F(8, 40) = 9.77$, $p = .0000$. Standard deviation of RP is presented in Figure 3.1 (bottom panel). Increases in pattern stability continued at a gradual rate from 8% on Day 3 to 15% on Day 5, and finally to 30% on Days 9 and 10, when compared to variability of the 90° RP pattern on Day 2. Percent improvement scores for SD of RP are illustrated in Figure 3.2. A significant block effect was also observed (SD of RP, $F(4, 20) = 9.49$, $p = .0001$). Performance of the 90° out-of-phase task showed a general increase in stability across blocks, whereby

Figure 3.1. RMSE of goal relative phase (top panel) and SD of RP (bottom panel) across 9 days of acquisition (Error bars = SEM).

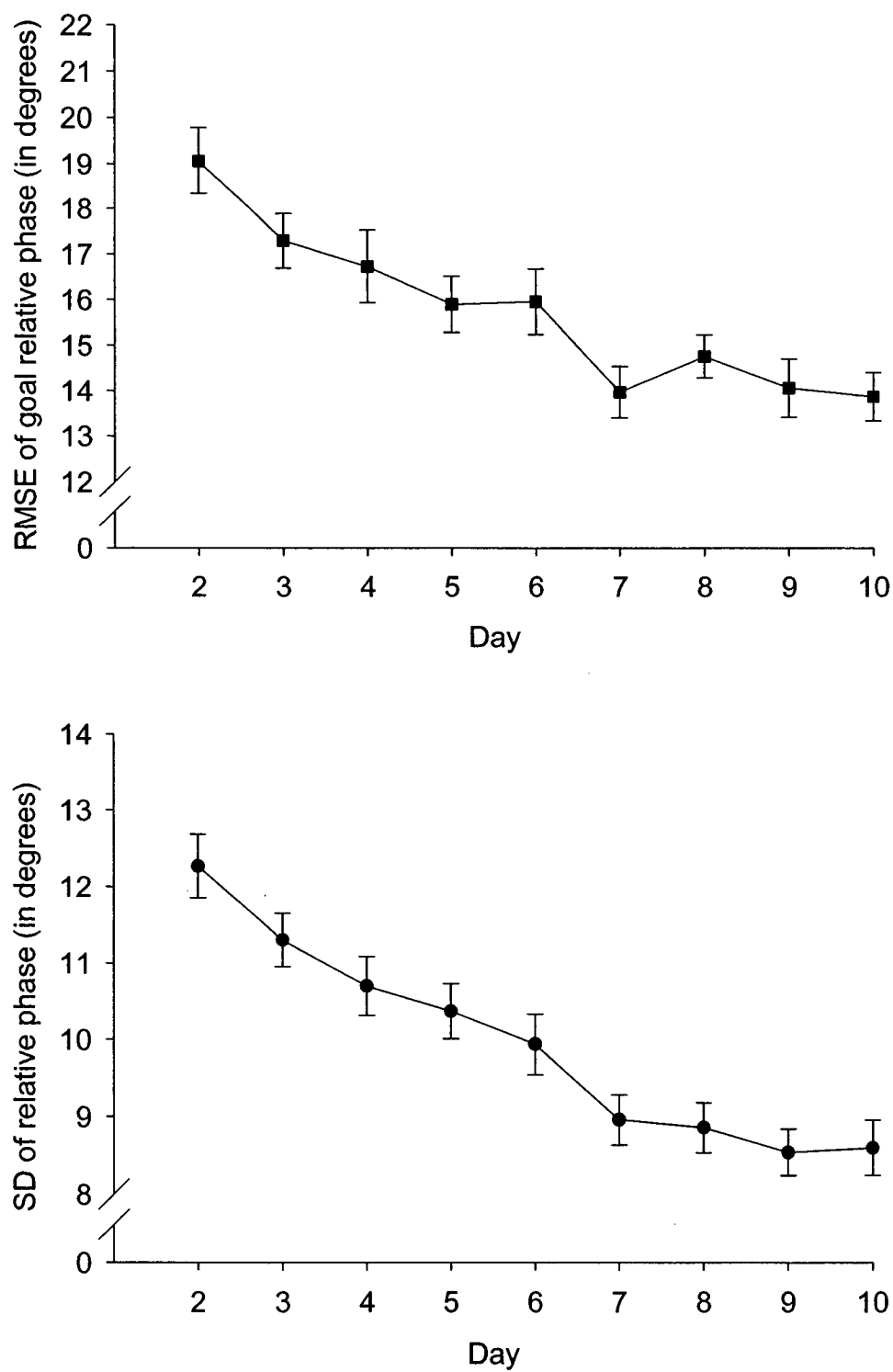
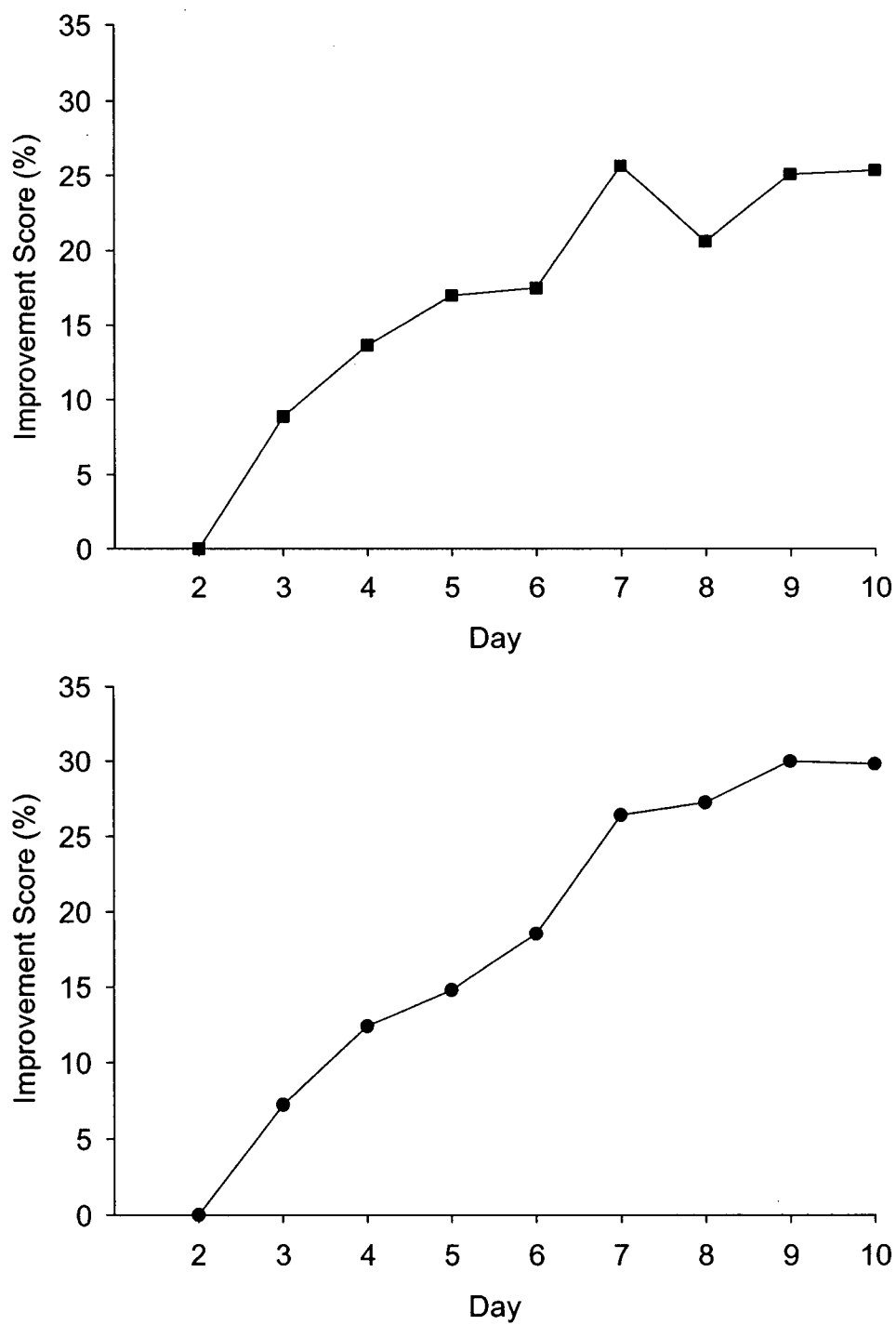


Figure 3.2. Percent Improvement from Day 2 for RMSE of goal relative phase (top panel) and SD of RP (bottom panel).



Blocks 2 ($\underline{M} = 10.1^\circ$, $\underline{SD} = 3.2^\circ$), 3 ($\underline{M} = 9.9^\circ$, $\underline{SD} = 3.0^\circ$), 4 ($\underline{M} = 9.7^\circ$, $\underline{SD} = 2.8^\circ$) and 5 ($\underline{M} = 9.3^\circ$, $\underline{SD} = 2.4^\circ$) were significantly more stable than Block 1 ($\underline{M} = 10.9^\circ$, $\underline{SD} = 3.4^\circ$).

Changes in Cycle Frequency across Acquisition. Cycle frequency was submitted to a $9 \times 2 \times 5$ (Day \times Segment \times Block) ANOVA, with repeated measures on all factors. Findings revealed no significant main effect for day ($p = .461$) or block ($p = .567$). Mean preferred rate of frequency was 0.5 Hz, and ranged from 0.40 to 0.70 Hz. On average, participants performed 6.5 movement cycles per trial.

Individual Performance Data. Of special interest is the learning strategy the individual self-employed to learn the 90° pattern. In contrast to Experiments 1 and 2, visual inspection of the Lissajous figures revealed that the majority of participants attempted to learn the phasing requirements by first making a box on the computer screen. This was accomplished by decoupling the limbs and moving each limb independently (see Figure 3.3 for a schematic illustration of the following description). First, the individual made a horizontal line across the screen by moving the right limb from the 'IN' to 'OUT' marker (panel A). This was followed by displacement of the left limb (flexion to extension), which produced the vertical component of the box configuration (panel B). A full square was completed by returning the right limb from the 'OUT' marker to the 'IN' marker (panel C), followed by the left limb (panel D). Once individuals could produce a square configuration, their focus shifted towards 'smoothing' or 'rounding' the corners of the box to create more of a circular shape. At this point, instead of momentarily stopping the limb at each reversal point, the individual attempted to keep the limbs moving continuously.

Figure 3.4 demonstrates the evolution of 90° RP performance across the first 100 trials for a participant employing the 'square box' strategy for learning the criterion pattern. On the very first trial of acquisition, the individual coordinates the limbs in an anti-phase mode of coordination. However, this influence is only temporary as the individual immediately attempts to uncouple the limbs, as demonstrated in Trial #5 by the high variability and widening of the Lissajous trace.

Figure 3.3. Schematic description of the 'box strategy' employed by participants to learn the 90° pattern.

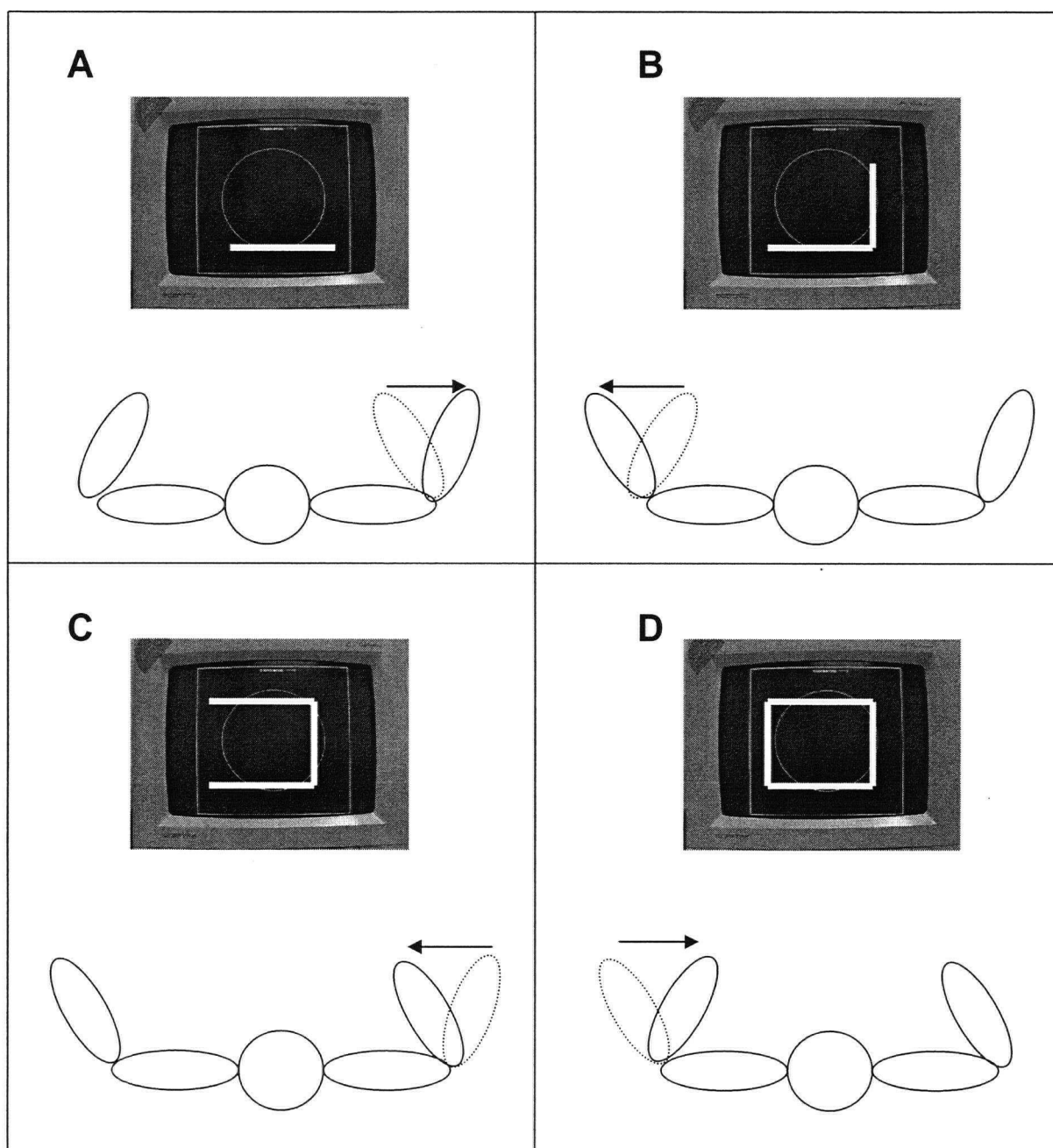
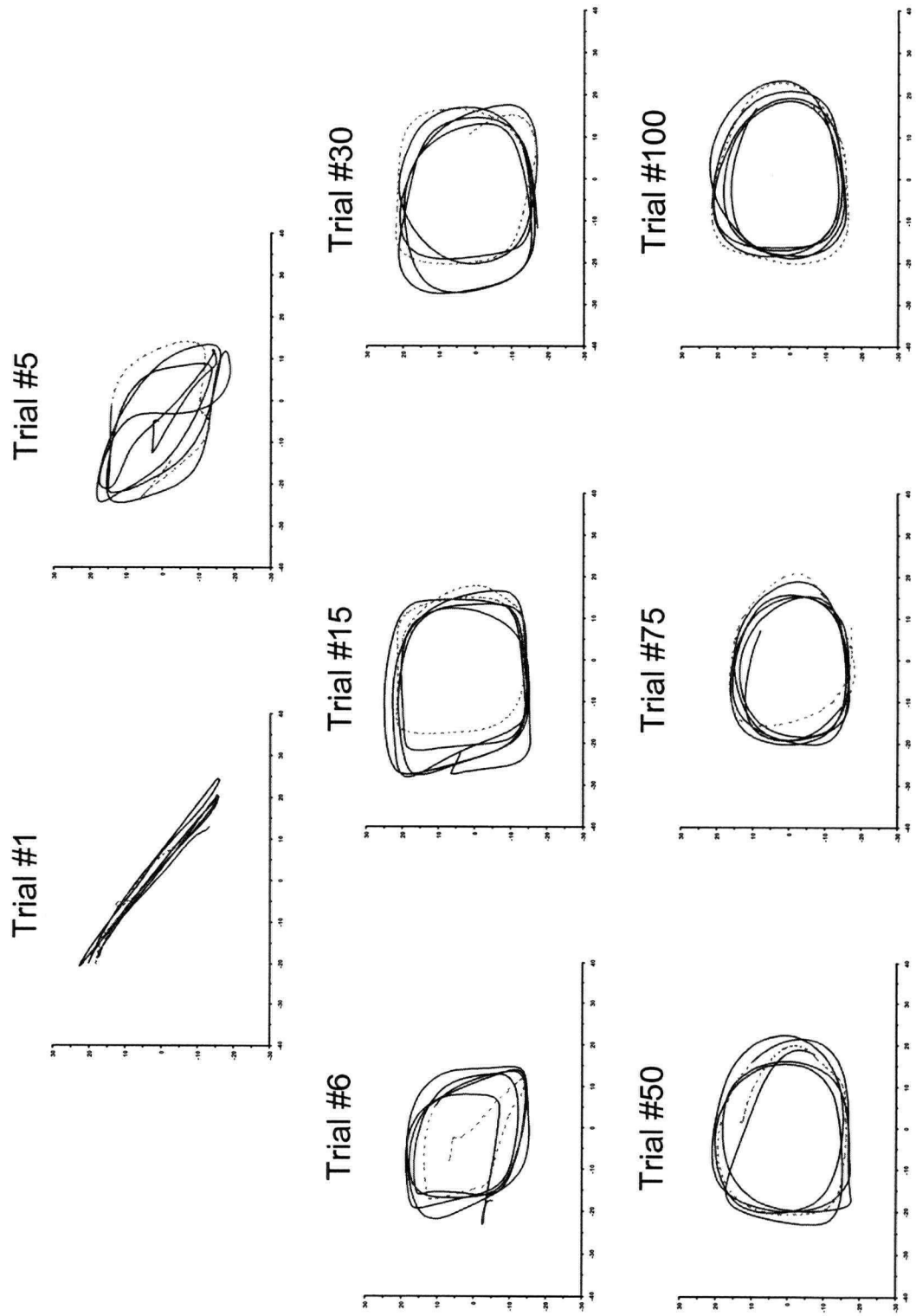


Figure 3.4. Individual trial data from Day 1 displayed as Lissajous figures for Participant 6. The solid line represents the no-vision segment, and the dotted line represents the vision segment (x-axis = right forearm displacement; y-axis = left forearm displacement).



By Trial #6, a square configuration emerged, which continued to increase in consistency and amplitude (Trial #15). By Trial #30, a configuration more circular in nature appeared. Improvements in accuracy and stability of the circle shape continued across practice. By the end of Day 1, the individual was able to produce a relatively accurate and consistent 90° pattern.

Performance of the 90° pattern improved with practice. The criterion task continued to improve in accuracy and stability over the final nine days of acquisition. These data also suggest that the use of servo torque motors influenced the strategies employed by participants to learn the new coordination pattern. Once again, cycle frequency did not increase from Days 2 to 10 of acquisition. Instead, participants generally maintained their self-selected frequency for the duration of the experiment, which happened to be the same frequency the servo torque motors moved at. Although mean cycle frequency in Experiments 1 and 2 were also slow (0.6 Hz and 0.7 Hz, respectively), individual data from the former investigations exhibited a greater range in selected movement frequency between participants in comparison to Experiment 3 (see Question 2, Table 3.1 of this chapter). Therefore, it is possible that rate of cycle frequency in the present investigation was influenced by the speed of the servo torque motors.

Question 2: Did Performance Differences Appear between Segments?

Changes in Pattern Accuracy and Stability across Acquisition. The dependent measures of RMSE and SD of RP were separately analysed by way of a 9 x 2 x 5 (Day x Segment x Block) ANOVA, with repeated measures on all factors (refer back to Question 1). Results showed that performance was more accurate, $F(1, 5) = 31.88$, $p = .002$, and more stable, $F(1, 5) = 249.08$, $p = .0000$, under visual feedback conditions (i.e., the 3 s segment), in comparison to performance in the absence of relative motion feedback (i.e., the 8.5 s segment) (see Figures 3.5 and 3.6). Inspection of mean RP values revealed that all participants performed within a

Figure 3.5. RMSE of goal relative phase for the no-vision (left panel) and the vision segment (right panel) across 9 days of acquisition (Error bars = SEM).

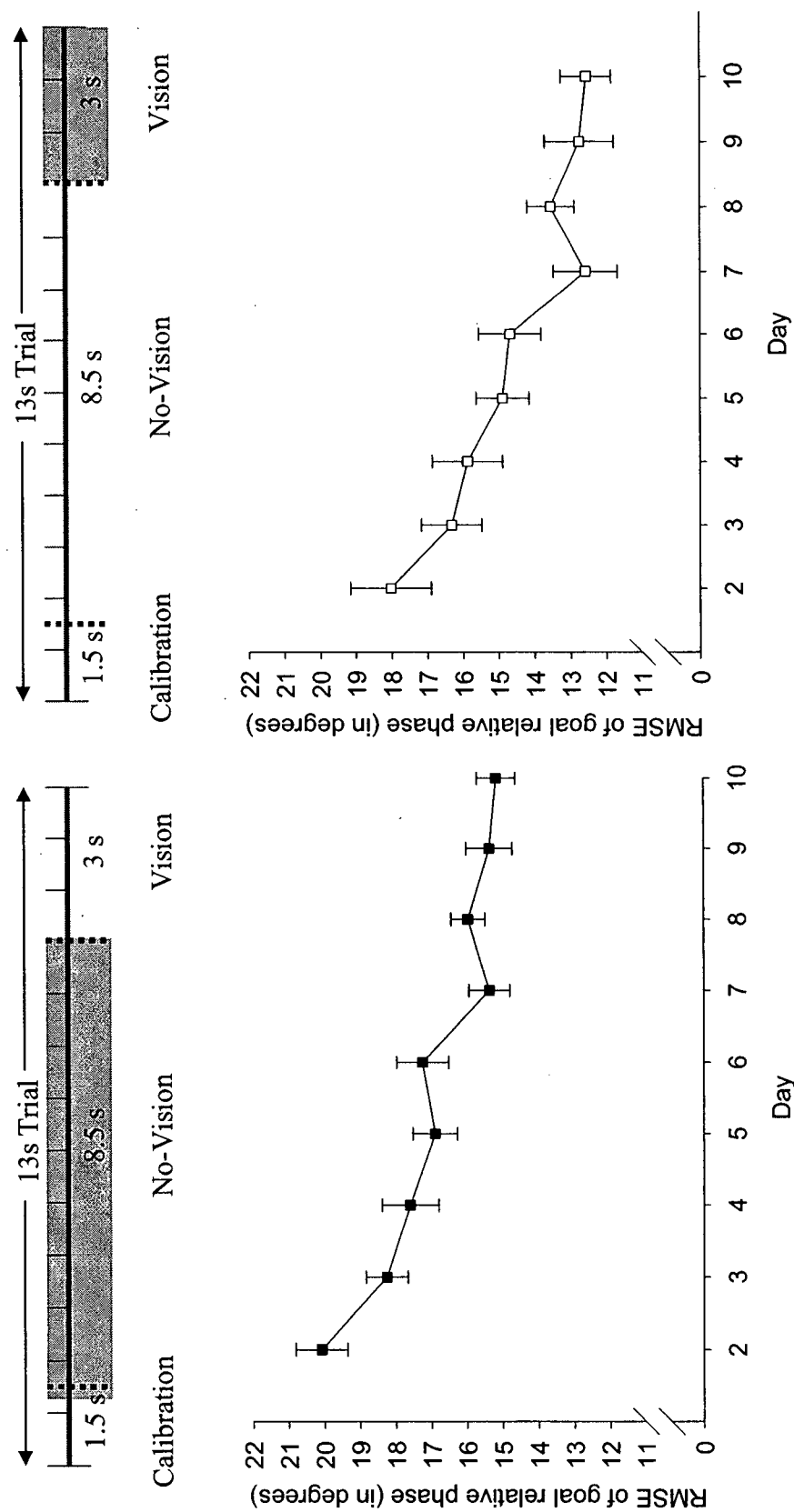
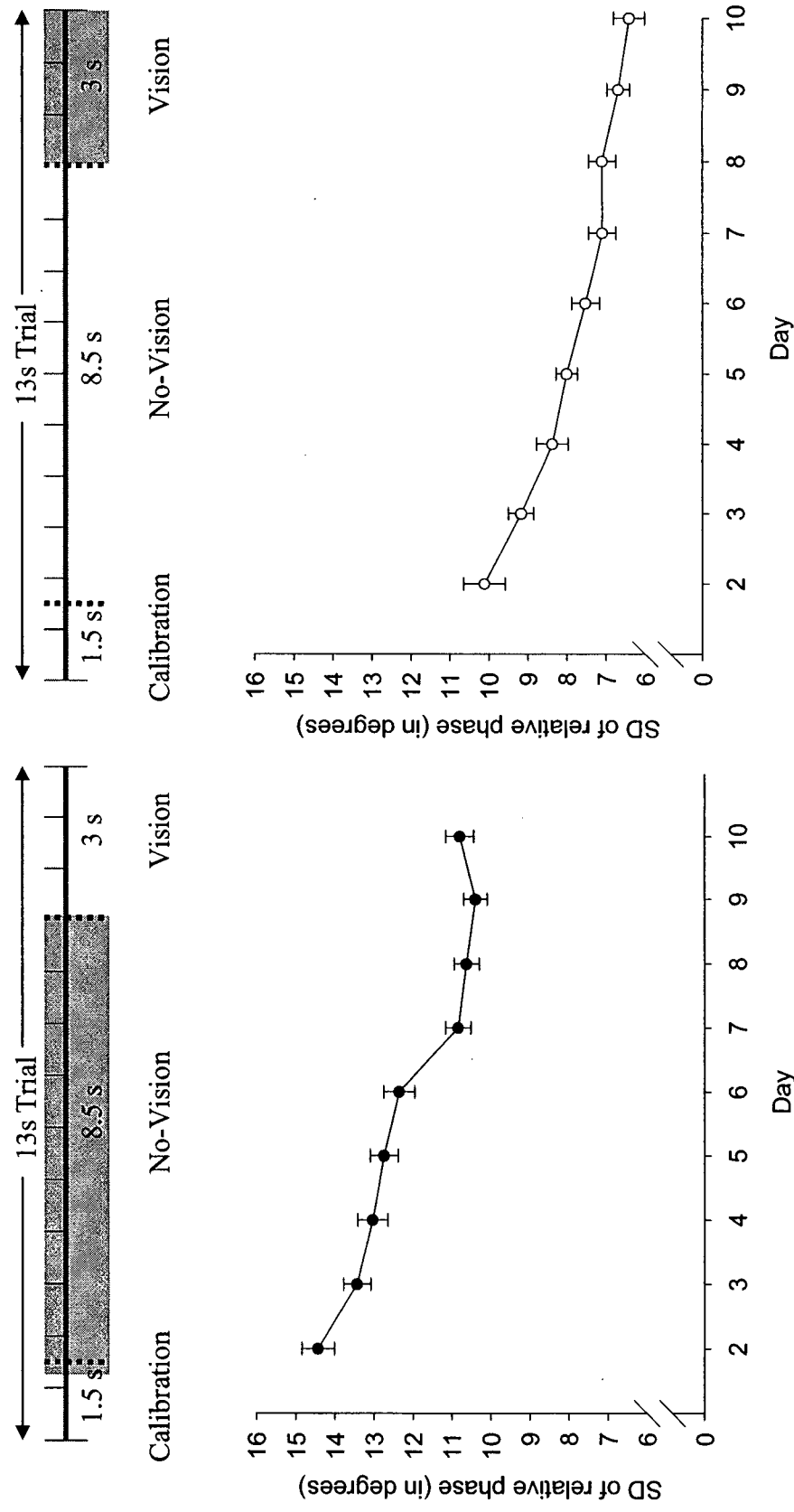


Figure 3.6. Standard deviation of relative phase for the no-vision (left panel) and the vision segment (right panel) across 9 days of acquisition (Error bars = SEM).



bandwidth of $\pm 10^\circ$ of the criterion pattern by the end of the third day of acquisition in both trial segments.

Cycle Frequency. No significant main effect occurred between segments for mean preferred cycling frequency ($p = .616$). Selected cycle frequency for the no-vision segment was 0.481 Hz, while mean movement frequency for the vision segment was 0.475 Hz (see Table 3.1).

Pattern Accuracy and Stability across Experiments. Acquisition data for each segment was examined in a Group (Experiment 1, Experiment 2, Experiment 3) x Day (9) x Block (5) ANOVA, with group as the between-subject factor. Experiment 1 was referred to as the enhanced feedback group (enhanced FB) because participants received relative motion feedback for 8.5 s of the segment. In contrast, Experiment 2 was referred to as the reduced feedback group (reduced FB) as they received concurrent visual feedback for the last 3 s of the trial only. Finally, the present investigation was referred to as the manual feedback group (manual FB) because servo torque motors, in addition to 3 s of concurrent visual feedback, passively moved participants' limbs. Separate analyses were conducted for RMSE and SD of RP.

RMSE of goal relative phase (top panel) and SD of RP (bottom panel) are presented in Figure 3.7. Each trial segment is plotted separately, whereby the left panel represents the 8.5 s segment and the right panel represents the 3 s segment. Analysis of the 8.5 s segment revealed a significant difference between groups for both RMSE, $F(2, 15) = 4.98$, $p = .021$, and SD of RP, $F(2, 15) = 6.15$, $p = .011$. The 90° pattern was performed with least error by the enhanced FB group ($\underline{M} = 9.4^\circ$, $\underline{SD} = 2.5^\circ$), followed by the manual FB group ($\underline{M} = 16.9^\circ$, $\underline{SD} = 5.0^\circ$) and reduced FB group ($\underline{M} = 25.9^\circ$, $\underline{SD} = 18.0^\circ$), respectively. With respect to SD of RP, the enhanced FB group and the manual FB group performed the required pattern with the least variability ($\underline{M} = 8.9^\circ$ and 12.1° ; $\underline{SD} = 2.4^\circ$ and 2.5° , respectively) in comparison to the reduced FB group ($\underline{M} = 19.2^\circ$, $\underline{SD} = 15.0^\circ$). Findings also revealed a significant day

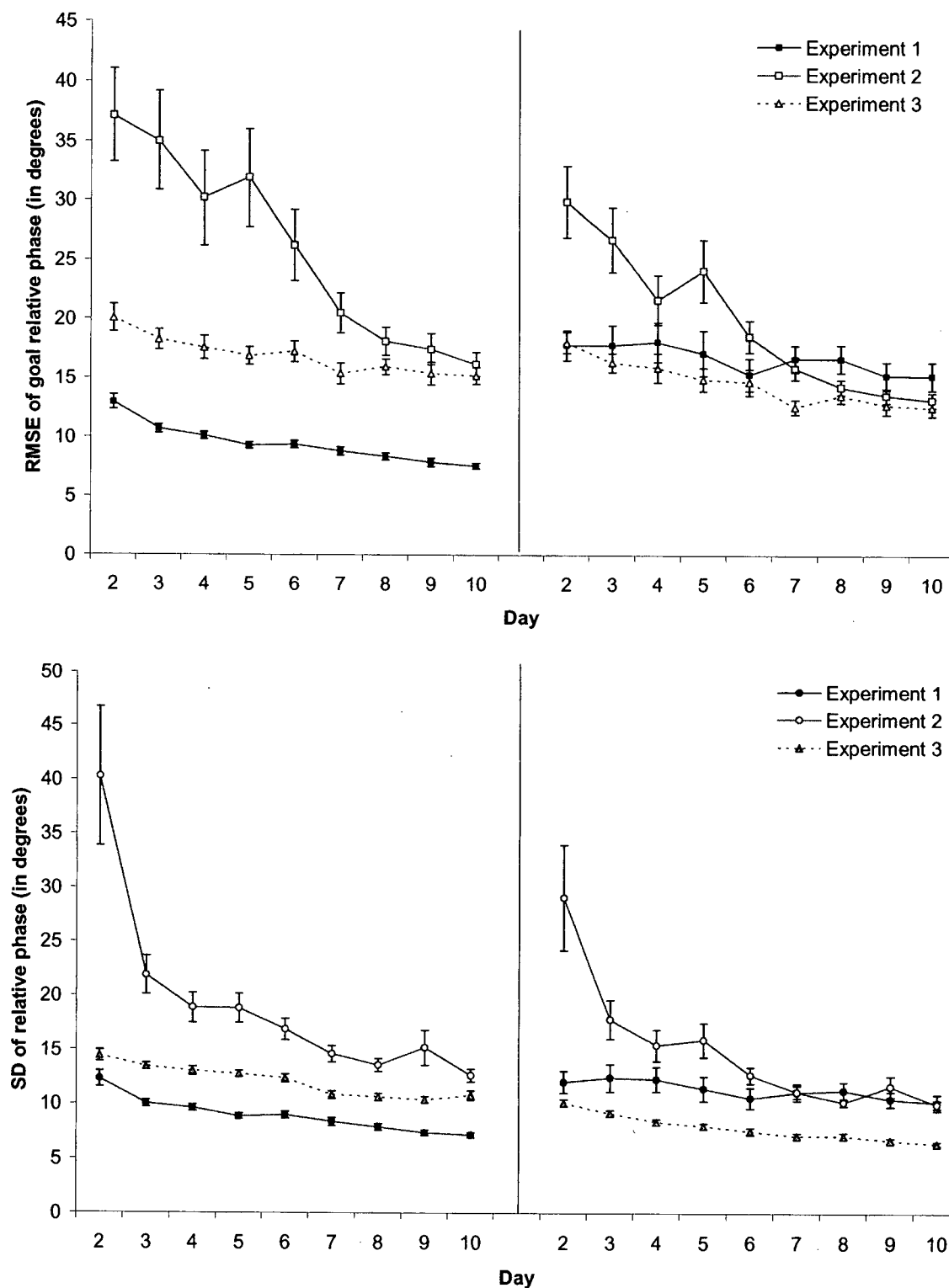
Table 3.1

Mean cycle frequency during the no-vision and vision segment for each participant collapsed across block.

		Day									
		1 ¹									
Participant	NV V	NV	V	NV	V	NV	V	NV	V	NV	V
		NV	V	NV	V	NV	V	NV	V	NV	V
1	0.5 0.6	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.5
2	0.5 0.7	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
3	0.5 0.5	0.5	0.4	0.5	0.5	0.5	0.4	0.5	0.5	0.4	0.4
4	0.5 0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4
5	0.5 0.7	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.5	0.4
6	0.5 0.4	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.4

¹ The shaded area represents data that were not included in the statistical analysis.

Figure 3.7. RMSE of goal relative phase (top panel) and SD of RP (bottom panel) plotted separately for each trial segment and compared across experiments. The left panel represents the 8.5 s segment and the right panel represents the 3 s segment (Error bars = SEM).



by group interaction for both pattern accuracy (RMSE, $F(16, 240) = 5.25$, $p = .0000$) and stability (SD of RP, $F(16, 240) = 4.23$, $p = .0000$). These interactions occurred because the reduced FB group made the greatest gains in performance across days. The provision of continuous relative motion feedback and manual guidance during the 8.5 s segment appeared to facilitate acquisition of the 90° pattern on the very first day of practice. By Day 2, participants in both the enhanced and manual FB groups had already made large gains in performance. Thus, further performance gains were smaller than the improvements observed for the reduced FB group across the final 9 days of practice.

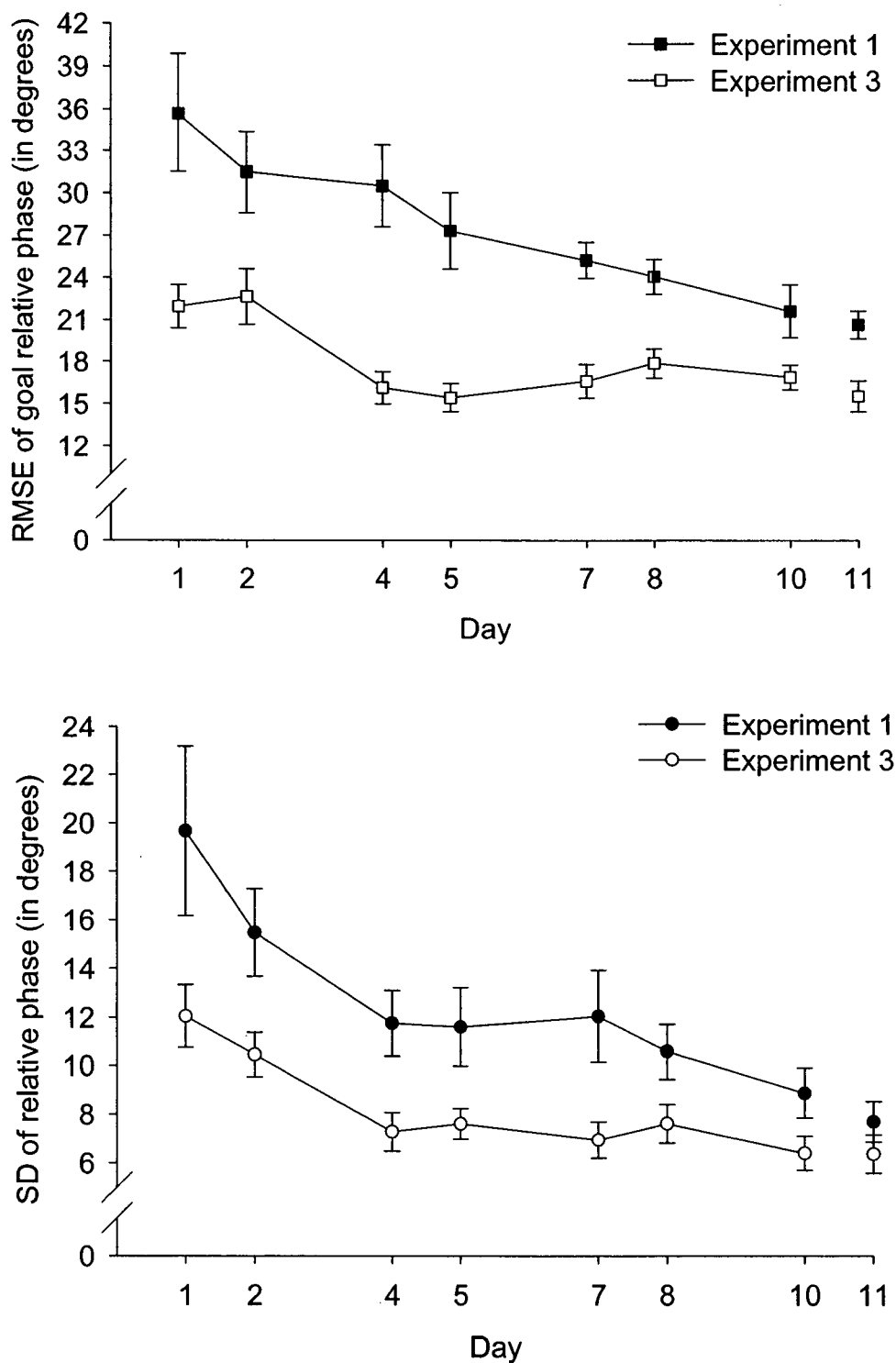
Analysis of the 3 s segment showed no significant differences between groups for both RMSE ($p = .461$) and SD of RP ($p = .083$). However, results did reveal a significant group by day interaction for both dependent measures (RMSE, $F(8, 120) = 8.69$, $p = .0000$; SD of RP, $F(16, 120) = 2.06$, $p = .014$). Once again the greatest gains in performance were exhibited by the reduced FB group in comparison to both the enhanced FB and manual FB groups.

Performance of the 90° pattern is superior in the presence of concurrent visual feedback. These data indicate that manual guidance had a beneficial effect on the learning of a new coordination pattern (in comparison to Experiment 2). However, accuracy and stability of the 90° out-of-phase task was generally superior when continuous visual feedback was available to guide performance in comparison to conditions without visual feedback.

Question 3: Did a Performance Advantage Emerge in No-Feedback Transfer Tests when Compared to Experiment 1?

Each dependent measure was submitted to an Experiment (FB Group: Enhanced, Manual) x Day (8) x Segment (2) x Block (5) mixed design ANOVA, with experiment as the between-subject factor. Figure 3.8 illustrates RMSE of goal relative phase (top panel) and SD of RP (bottom panel) for Experiment 1 versus 3. Performance improved for both groups with practice, as indicated by a significant

Figure 3.8. RMSE of goal relative phase (top panel) and SD of RP (bottom panel) for immediate and delayed no-feedback transfer tests across days and experiment (Error bars= SEM).



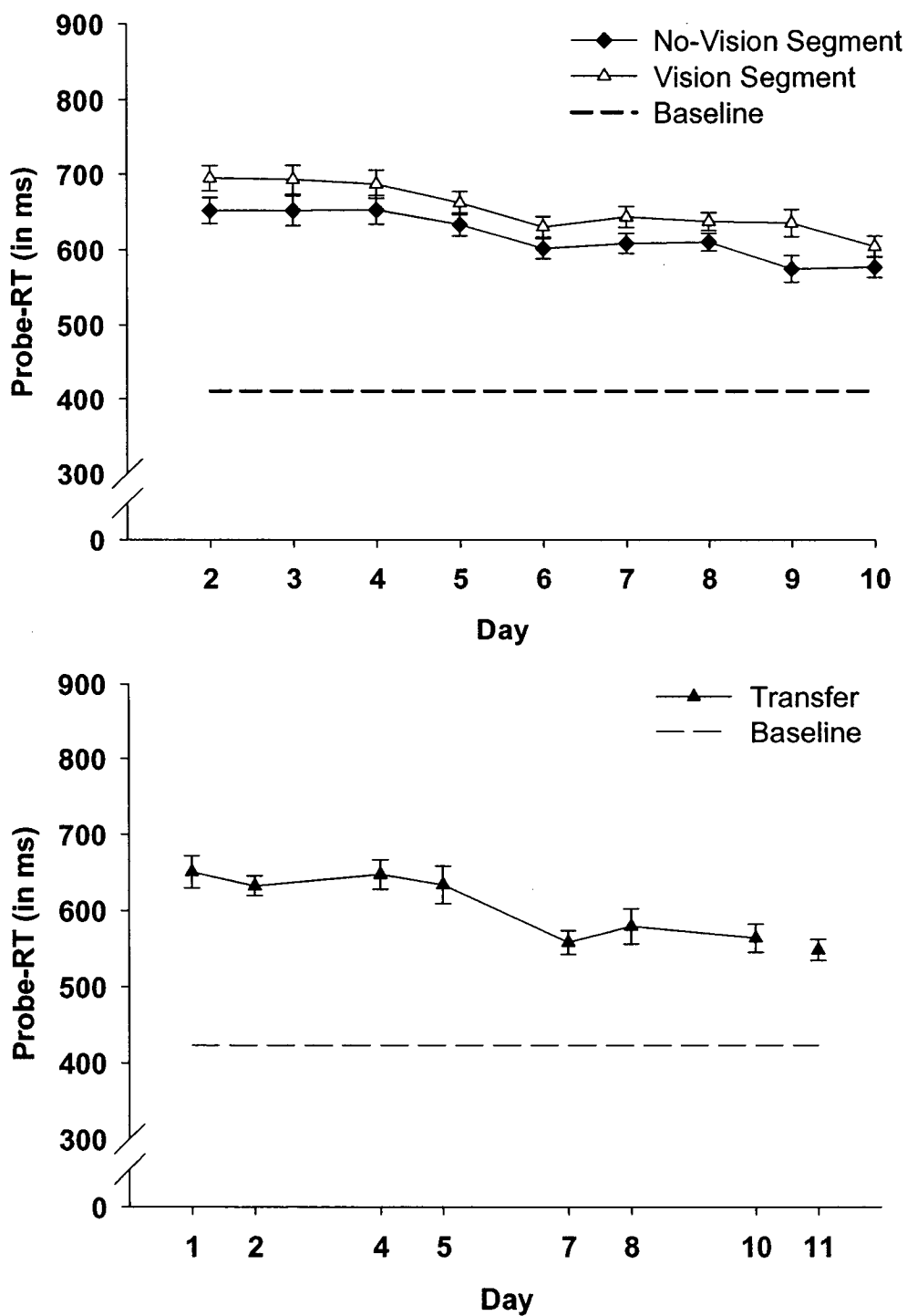
day effect for RMSE, $F(7, 70) = 4.09$, $p = .0008$, and SD of RP, $F(7, 70) = 5.73$, $p = .0000$. Results also revealed a significant difference between groups for RMSE, $F(1, 10) = 5.38$, $p = .043$. Mean RMSE was significantly lower for the manual FB group ($M = 17.9^\circ$, $SD = 6.7^\circ$) when compared to the enhanced FB group ($M = 27.1^\circ$, $SD = 13.0^\circ$). In addition, performance of the 90° pattern was generally less variable for the manual FB group ($M = 8.1^\circ$, $SD = 4.6^\circ$), as compared to the enhanced FB group ($M = 12.1^\circ$, $SD = 9.5^\circ$), but did not reach statistical significance ($p = .061$). These data demonstrate that a performance advantage emerged in the no-feedback transfer tests for learners receiving manual guidance in lieu of extended availability of continuous on-line feedback.

Question 4: Did Extended Practice on a Bimanual Coordination Task Reduce and Eventually Eliminate Dual-Task Interference?

Probe-RT during Acquisition. Following preliminary analysis², the probe data were submitted to a Day (9) x Segment (no-vision, vision) x Task Condition (acquisition probe-RT, baseline RT) x Probe position (4) ANOVA, with repeated measures on all factors. A one-way repeated measures ANOVA revealed no significant difference between pre-acquisition ($M = 426$ ms; $SD = 99$ ms) and post-acquisition ($M = 400$ ms; $SD = 89$ ms) measures of baseline RT ($p = .221$). Therefore, mean RT for the secondary task baseline condition was calculated from both measures ($M = 411$ ms; $SD = 95$ ms), and used for all cells of the baseline condition in the ANOVA.

Figure 3.9 (top panel) presents mean probe-RT for each segment across days compared to baseline RT. Results revealed a significant two-way interaction for day x task condition, $F(8, 40) = 7.19$, $p = .000$, and segment x task condition, $F(1, 5) = 2.70$, $p = .018$. Probe-RT decreased from 674 ms ($SD = 122$ ms) on Day 2 to 591 ms ($SD = 113$ ms) on Day 10, but did not reach baseline levels. These observations were confirmed by significant main effects for day, $F(8, 40) = 2.70$, $p = .018$, and condition, $F(1, 5) = 53.92$, $p = .0007$. Post-hoc analysis showed that probe-RT on Day 10 was significantly faster than probe-RT on Days 2, 3 and 4. Further post-hoc

Figure 3.9. Mean probe-RT for acquisition (top panel) and transfer (bottom panel) plotted as a function of day and compared to baseline RT ($M = 411$ ms) (Error bars = SEM).



analysis of the segment x task condition interaction demonstrated that probe-RT was significantly faster in the no-vision (8.5 s) segment ($M = 618$ ms, $SD = 112$ ms) as compared to the vision (3 s) segment ($M = 655$ ms, $SD = 126$ ms), and both segments were significantly different than baseline RT. No significant main effect was found for probe position ($p = .292$).

Probe-RT during Transfer. The data were submitted to a Condition (transfer probe-RT, baseline RT) x Day (8) x Probe (4) ANOVA, with repeated measures on all factors. Figure 3.9 (bottom panel) displays mean probe-RT under transfer conditions compared to baseline RT. Findings revealed a significant main effect for condition, $F(1, 5) = 46.49$, $p = .001$, and day, $F(7, 35) = 11.09$, $p = .0000$, as well as a significant interaction effect for condition x day, $F(7, 35) = 11.09$, $p = .0000$. Mean probe-RT improved across transfer tests from 707 ms ($SD = 104$ ms) on Day 1 to 593 ms ($SD = 114$ ms) and 539 ms ($SD = 122$ ms) on Days 10 and 11, respectively. Despite these improvements, post-hoc analysis revealed that mean probe-RT was significantly slower than baseline RT on each day of transfer. There was no main effect for probe position ($p = .446$).

Performance of a 90° out-of-phase task remains attention demanding following extended practice. Identical to our previous investigations, these findings demonstrated a central attentional cost when responding to a discrete secondary probe during the simultaneous performance of a 90° out-of-phase task. Reaction time to the probe decreased from Day 1 to Day 10, but never reached RT measures collected when responding to the auditory probe alone. Results also showed that the attention demands of the 90° pattern were greatest when visual feedback was available to guide performance, as compared to performance in the absence of on-line relative motion feedback.

Discussion

The purpose of the present investigation was to examine the effects of manual guidance for learning a 90° out-of-phase bimanual coordination pattern. Results demonstrated that using servo torque motors to physically guide the learner's limbs provided some learning benefits for acquiring the new relative phase task. In comparison to Experiment 2, all participants were able to coordinate the limbs near a phase offset of 90° much earlier in the learning process. Given that the only difference between Experiments 2 and 3 was the addition of manual guidance, we suggest that the servo torque motors provided the learner with a general idea of the task requirements. This occurred by giving the learner an indication of how each limb should move in relation to the other to produce a phase offset of 90°. This is important when instructions regarding how to produce the criterion task are not provided. For some individuals, manual guidance may have enabled the learner to produce the required pattern, which otherwise he or she may not have been able to effectively produce until later stages of learning, or not at all.

Although individuals were passively moved by the servo torque motors in the required phase offset, they also received motor playback of their own movements. This was advantageous in that learners were provided the opportunity to make direct comparisons between their movements and the criterion pattern. The participant not only experienced making the error, but also received sensory feedback regarding the error. The individual was then free to generate a movement solution on the subsequent trial. This problem-solving experience may have contributed to the effectiveness of manual guidance in learning a new coordination pattern (see Tsutsui & Imanaka, 2003).

Visual inspection of the relative motion plots showed that the servo torque motors influenced the type of strategy the individual employed to learn the new pattern. Although the movement of each manipulandum was smoothed as much as possible, to give a natural sinusoidal movement profile, the resulting servo motor movements may have appeared "robotic", with a triangular movement profile. The main characteristic of a triangular movement profile is very high acceleration at movement reversals and low acceleration 'coasting' between transitions. High-

acceleration movement reversals resulted in the majority of participants using a triangular movement profile (i.e., the 'square box' strategy) to learn the phasing requirements of the task – a strategy that did not spontaneously emerge in any of our previous investigations. It remains unclear, however, whether movement of the servo torque motors prompted participants to make a concerted effort to decouple the limbs on their own accord, or whether they were merely trying to imitate the movements of the manipulandum. Nonetheless, the high-acceleration movement reversals by the torque the motors did influence the phase relation between the right and left forearms.

The cycle frequency of the servo torque motors may also have influenced the participants selected movement frequency. Although participants have shown a tendency to move at a frequency of less than 1 Hz (Experiments 1 & 2), all participants in the present study moved at a frequency of approximately 0.5 Hz, the same frequency the servo torque motors moved at. This occurred despite initial instructions to individuals stressing that they could move at their own self-selected frequency. An obvious suggestion for future research would be to increase the frequency of the torque motors to examine the effects on learning a new bimanual coordination pattern¹.

Despite the benefits of manual guidance, performance in the no-vision segment did not reach the same levels of performance displayed in the vision segment. This finding has been demonstrated in all three of our experiments, which leads us to conclude that performance of the 90° task is more successful when concurrent visual feedback of the criterion pattern is available to direct performance. Under visual conditions, participants are provided information regarding the displacement of each limb as it moves in real-time. This facilitates the learning of a new coordination pattern because the relative motion plot identifies the task goal, and provides learners with non-prescriptive feedback alerting them to the properties and relationships inherent within the task. This specifies how the system can be controlled without specific instructions on how to achieve the required pattern. However, the biggest benefit of manual guidance may be with respect to transfer. Performance of the 90° pattern transferred most successfully to conditions of no-

feedback for participants in the present experiment, in comparison to Experiment 1. Therefore, these data suggest that supplementing the learning environment with proprioceptive information may benefit performance when concurrent visual feedback is no longer available to guide performance. In light of increasing evidence emphasizing the importance of proprioception for interlimb coordination (e.g., Baldissera, Cavallari, & Tesio, 1994), further investigation into the benefits of manual guidance as an instructional aid are clearly warranted.

With respect to attention demands, the present investigation supported the findings of both Experiments 1 and 2. Performance of a 90° out-of-phase task incurred an attentional cost, even after extended periods of task-specific practice. Results also revealed that reaction time to a secondary probe was faster when performing the criterion task in the absence of real-time feedback, in comparison to reaction time collected when visual feedback was available to guide performance. Similar to our two previous investigations, these data support the idea that attention demands increase when the learner is required to switch between feedback sources within a trial. This occurs irrespective of whether the transition is from a proprioceptive feedback source to a visual feedback source, or vice-versa.

Chapter Footnotes

- 1 In pilot work, the servo torque motors were originally set at a frequency of 1 Hz. However, at this speed the manipulanda began to vibrate noticeably and the movements of the torque motors were extremely jerky. Therefore, we traded-off speed for increased smoothness of movement.
- 2 A preliminary analysis was conducted to verify that performance of the 90° pattern was maintained on trials where a probe occurred, in comparison to no-probe trials. RMSE was calculated and submitted to a Trial Type (no-probe, probe) x Day (9) repeated measures ANOVA. Findings revealed no significant difference for trial type ($p = .224$). Mean RMSE was 15.8° for the no-probe trials and 14.8° for the probe trials. A Time (pre-probe, post-probe) x Day (9) repeated measures ANOVA was also administered to verify that performance of the 90° pattern was the same 1 cycle before and 1 cycle after the probe. Results showed no significant difference ($p = .679$) in RMSE prior to ($M = 14.1^\circ$) and following an auditory probe ($M = 14.0^\circ$). These data confirm that participants maintained attentional priority on the 90° out-of-phase task.

CHAPTER IV

EXPERIMENT 4

Attention Demands and the Performance of Intrinsic and Learned Bimanual Coordination Patterns

Introduction

The primary purpose of the preceding line of investigations was to examine changes in attention demands during the learning of a new bimanual coordination task. More specifically, acquisition of the 90° pattern was investigated over the time course of extended learning episodes and under different conditions of continuous visual feedback. In each of the three experiments, we found that voluntary stabilization of a newly learned bimanual coordination task incurred an attentional cost even after extended periods of task-specific practice. In the present investigation, we asked participants to return to the laboratory to perform the bimanual coordination patterns of in-phase and anti-phase. The purpose of this experiment was to examine the attentional costs associated with maintaining performance of pre-existing coordination tendencies in comparison to the newly learned bimanual coordination task of 90° RP. The coordination states of in-phase and anti-phase were chosen because they are intrinsic patterns of the human motor system, and can be performed skilfully, without practice (Kelso, 1984) (*refer to Appendix A - Motor Dynamics: Fundamental Concepts and Terminology*). We were primarily interested in examining whether dual-task interference is eliminated when performing coordination patterns thought to be highly automatic in nature (also see Lee, Wishart, & Murdoch, 2002).

Attention Demands of Preferred Coordination Tendencies

According to the dynamical systems perspective, smooth coordinated behaviour emerges from a mutual coupling between the components of the system. At a behavioural level, this is captured by the dynamics of relative phase, which results from a nonlinear coupling between the homologous limbs that specifies the positioning and velocity of each limb relative to the other. To determine the motion of

each limb in space and time, it is further proposed that an informational linkage exists between the limbs, which serve to inform each limb of the contralateral limb's whereabouts (see Temprado, Zanone, Monno, & Laurent, 1999). This informational linkage is mediated by the central nervous system (CNS). Conceptually, the CNS contributes to the coordination dynamics in controlling (or linking) the limbs, so that required patterns may be assembled and stabilized (Schöner & Kelso, 1988).

This informational linkage has been recently viewed as an 'energy expense' necessary for maintaining coordination at a given frequency. The energy involved in stabilizing the system (determined at the behavioural level by fluctuations of relative phase) may be viewed in terms of mechanic and metabolic energy, as well as some kind of 'mental energy' or 'effort' devoted by the CNS to perform a preferred pattern of coordination. Referred to as attentional load, research has recently focused on assessing the relationship between coordination dynamics and the attentional activity of the CNS – concepts originally considered to be irreconcilable (see Swinnen & Carson, 2002 for a historical perspective on interlimb coordination). It is postulated that attention measures provide an approximate index of the coordinative activity of the CNS. As such, the focus of much of this work is on understanding the central costs incurred by the CNS to stabilize coordination patterns against perturbing forces.

As previously discussed (see Experiment 1), attentional load is typically assessed using a dual-task paradigm, whereby participants simultaneously perform a bimanual coordination task (i.e., in-phase or anti-phase) and a discrete RT task. Moreover, participants are instructed to maximize the stability of the required pattern by giving attentional priority to the coordination task, which serves to increase the amount of attentional resources allocated to its performance. As a result, it is hypothesized that coupling strength will be maintained or increased (as measured by the collective variable of relative phase), while available resources to the secondary task are depleted (as indicated by increases in RT).

Using the dual-task paradigm, Temprado et al. (1999) provided empirical evidence showing that intrinsic coordination patterns can be intentionally stabilized, improving performance beyond the level of stability attained spontaneously (i.e.,

when no special attention was given to the coordination task). Moreover, this extra stabilization was shown to increase the coordinative activity of the CNS, leading to a performance trade-off between relative phase variability and RT. Findings also revealed that attentional cost was dependent on the respective stability of the pattern. Assembling and maintaining the required pattern at a given level of stability was less attention demanding the more stable the pattern. As such, Temprado et al. found a greater performance trade-off between relative phase variability and RT for anti-phase coordination than for in-phase coordination (also see Monno, Chardenon, Temprado, Zanone, & Laurent, 2000; Zanone, Monno, Temprado, & Laurent, 2001). A tentative origin for the high cost incurred in maintaining the anti-phase pattern can be explained by the recent work of Mayville, Bressler, Fuchs, and Kelso (1999) who examined activation of primary sensorimotor areas while executing preferred coordination tendencies. Results revealed that the execution of in-phase and anti-phase patterns involved activation of parietal and frontal cortical areas. However, to sustain performance of anti-phase coordination, greater activation of the sensorimotor areas was demonstrated.

A dual-task paradigm was employed in the present investigation to examine the attentional costs associated with performance of the preferred patterns of in-phase and anti-phase. Participants engaged in one session of 160 performance trials, which was comprised of 80 trials for the in-phase pattern and 80 trials for the anti-phase pattern. During the performance of in-phase or anti-phase, participants were required to vocally respond to a randomly computer-generated auditory signal on one-third of trials. Participants were instructed to maximize performance on the required pattern by giving attentional priority to the coordination task. Stability of the coordination pattern was quantified by the collective variable relative phase, whereas RT to the secondary task was used as an index of the central processing activity needed to maintain a coordination pattern at a given level of stability. Both primary and secondary task performance for in-phase and anti-phase modes of coordination were then compared to performance of the 90° out-of-phase task collected on the final day of practice in our three previous investigations (i.e., Experiments 1, 2, 3). The primary purpose of this analysis was to compare central

costs associated with intentional stabilization of a newly learned coordination pattern to bimanual coordination patterns that are inherently stable.

Since participants were asked to give attentional priority to the coordination task, it was hypothesized that RT should be slower in the dual-task condition, when compared to RT values obtained when performing the secondary task alone. Furthermore, the central costs associated with stabilizing each coordination tendency were predicted to be smaller for the in-phase pattern, compared to the anti-phase pattern because in-phase is demonstrated to be a preferred (more stable) mode of coordination. Therefore, in-phase coordination is less costly to the CNS when compared to anti-phase performance. In keeping with this rationale, in-phase coordination is also predicted to be less costly to stabilize when compared to stabilization of the newly learned 90° pattern.

Method

Participants

Ten participants were recruited from our three previous investigations: Experiment 1 ($n = 4$), Experiment 2 ($n = 3$) and Experiment 3 ($n = 3$). All participants had formerly received 1,000 practice trials where the goal relative phase was an offset of 90°; however, participants were exposed to different types of experience at the 90° task depending on which experiment they were recruited from. Individuals participating in Experiment 1 were provided concurrent information feedback of the relative motions of their limbs for 10 s of every 13 s practice trial, while participants from Experiments 2 and 3 received concurrent feedback for only 4.5 s of each 13 s trial. In addition, the limbs of each individual participating in Experiment 3 were also moved passively in the required relative phasing following each practice trial by servo torque motors.

Although participants had substantial experience with the 90° RP task, they were naïve to the purpose of the present experiment ($n = 8$ females; $n = 2$ males). The mean age of participants was 28.5 years ($SD = 6.0$; range = 24-44). All individuals signed informed consent forms prior to the experiment and upon completion received remuneration for participation. The experiment was carried out

according to the ethical guidelines set by the University Behavioural Sciences Screening Committee for research involving human participation at the University of British Columbia.

Primary Task and Apparatus

Using the same apparatus described in Experiment 1, the goal of the task was to flex and extend the limbs in either an in-phase or an anti-phase pattern of coordination in the horizontal plane. Displacement of the right limb resulted in horizontal movements on the screen, while displacement of the left limb resulted in vertical movements on the screen. Concurrent visual feedback was provided on the computer monitor for each participant by plotting the real-time displacement of the right limb on the ordinate against the displacement of the left-limb on the abscissa superimposed onto the template of the criterion task. This plot was referred to as a Lissajous figure.

When the limbs were correctly moved in 0° of relative phase, a diagonal line between the lower left and upper right corners of the computer screen was produced (Figure 4.1, panel A). Conversely, a diagonal line between the lower right and upper left portions of the screen was displayed for 180° of relative phase (Figure 4.1, panel B).

Secondary Task and Apparatus

While performing the task, participants were required to emit a vocal response if at any time an auditory 'beep' sounded. The apparatus used to generate and present the auditory signal, as well as the microphone used to pick-up the participant's vocal response, was the same as previously described in Experiment 1.

Procedure

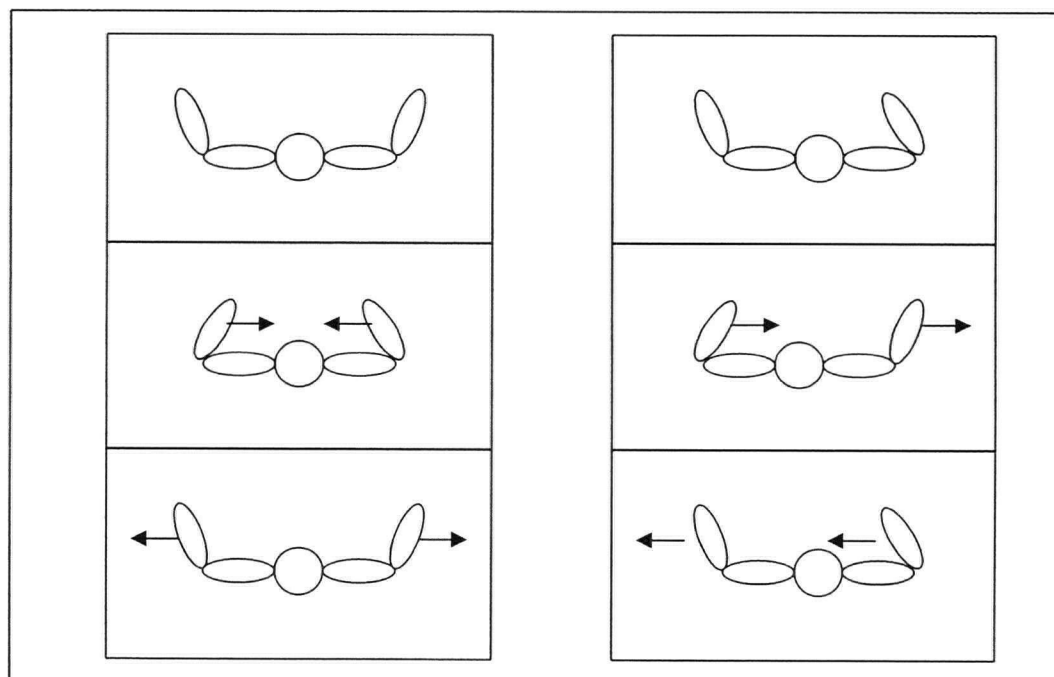
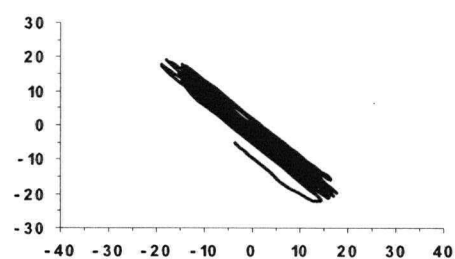
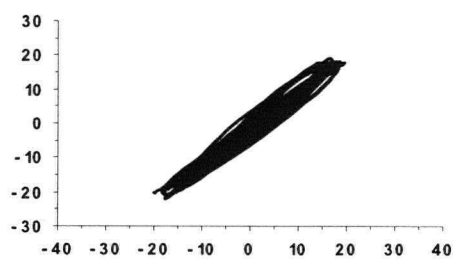
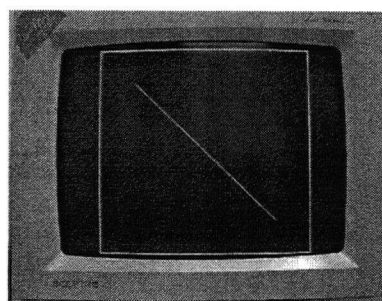
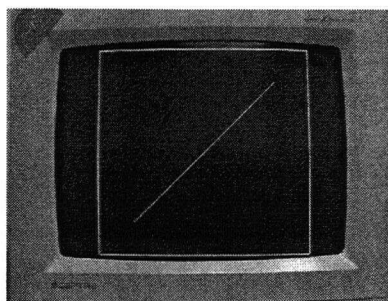
The present experiment consisted of one testing session in which participants performed a total of 80 in-phase trials and 80 anti-phase trials. All participants executed the 80 trials of each coordination mode in 2 sets of 40 trials, which was further subdivided into 4 blocks of 10 trials. Half of the participants performed in an

Figure 4.1. Illustration of in-phase and anti-phase coordination.

(Top panel) A visual presentation of the Lissajous templates for in-phase and anti-phase patterns of coordination, respectively.

(Middle panel) Performance of in-phase and anti-phase, respectively, plotted in the form of a Lissajous figure.

(Bottom panel) A schematic diagram depicting limb movements for in-phase and anti-phase patterns of coordination, respectively.



in-phase set first, while the other half received an anti-phase set first. Subsequent presentation of the coordination sets alternated between in-phase and anti-phase. All trials were 13 s in duration.

At the beginning of the session, participants were given an opportunity to re-familiarize themselves with the apparatus. Criterion templates representing in-phase and anti-phase patterns of coordination were then displayed on the screen, one after the other. Participants were informed that they could match the criterion template by moving the limbs in a particular phase relation. When the template for in-phase was displayed on the computer screen, participants were informed that they could achieve the pattern by coordinating the limbs so that they moved symmetrically in opposite directions between the two boundary markers. When the template representing the coordination state of anti-phase was displayed, participants were told that this pattern was accomplished by moving the limbs in alternating fashion (like a windshield wiper) in the same direction. Using the same instructions provided in the previous experiments, participants were told that they could move at their own pace, but the goal of the task was to produce continuous movement cycles within each trial that matched as closely as possible to the criterion template. One movement cycle was explained to consist of the moving distance between the boundary markers so that each hand returned to the same starting position.

Participants were also informed that they would receive the same augmented feedback schedule previously provided to them while learning the 90° RP task. Specifically, four participants (Experiment 1) received concurrent visual feedback for the first ten seconds of the trial, and then no feedback for the final three seconds. This group of participants was referred to as the Vision group. In contrast, six participants (Experiments 2 and 3¹) received concurrent feedback for initial calibration to the screen (1.5 s), as well as for the final 3 s segment. Visual feedback was removed for the middle (8.5 s) segment of the trial. This group was referred to as the No-Vision group. For all individuals, terminal feedback was provided immediately following the trial, which displayed the participants' performance during their respective no-vision segment against their performance in the vision segment.

This information was superimposed (in different colours) on the criterion template in the form of a Lissajous figure.

If the stimulus for the secondary task occurred during the trial, participants were instructed to respond by saying the word 'pop' as quickly as possible. Furthermore, participants were informed that there was the potential of only one probe to occur in a trial. Instructions also stressed that performance of the coordination pattern should be given maximal priority. For each coordination pattern, auditory probes occurred on 30 of the 80 trials. Twenty-two of the probes occurred at variable times during the first ten seconds of the trial, while 8 probes occurred in the last 3 seconds. Probes were presented randomly for each participant across the session.

Prior to, and at the end of acquisition, each participant performed 15 control trials during which RT to the auditory tone were collected in the absence of the primary task. This measure served as the baseline measure of RT. Baseline RT were collected for later comparison to probe-RT gathered during experimental trials, as well as baseline RT collected from Experiments 1-3.

Data Analyses

Performance of Bimanual Coordination Patterns

To assess the performance of the coordination task, continuous measures of relative phase (RP) were calculated (see Experiment 1). From the relative phase values, the standard deviation around the mean relative phase (SD of RP) was computed to obtain an estimate of the variability in relative phase. To provide an overall measure of performance error, root-mean-square error (RMSE) was calculated. Finally, cycle frequency was also computed to determine the average self-paced frequency of each movement cycle on every trial.

Central Costs

Reaction time (in ms) was measured as the interval between the onset of the auditory stimulus and the moment at which the microphone detected the

participants' vocal response. To determine baseline RT, a mean RT was determined for pre- and post- acquisition control conditions and submitted to a one-way repeated measures analysis of variance (ANOVA). No significant difference was found between pre-test ($M = 440$ ms, $SD = 86$ ms) and post-test ($M = 480$ ms, $SD = 118$ ms) baseline RT ($p = .064$)². Therefore, mean RT for the secondary task control condition was calculated using both pre- and post-test measures and then compared to participants' baseline RT time from the respective investigations collected previously. A one-way repeated measures ANOVA revealed no significant difference in baseline RT across experiments ($p = .226$). Mean RT for the secondary task control condition was then calculated using all baseline probe-RT measures obtained across experiments for each participant ($M = 442$ ms; $SD = 95$ ms).

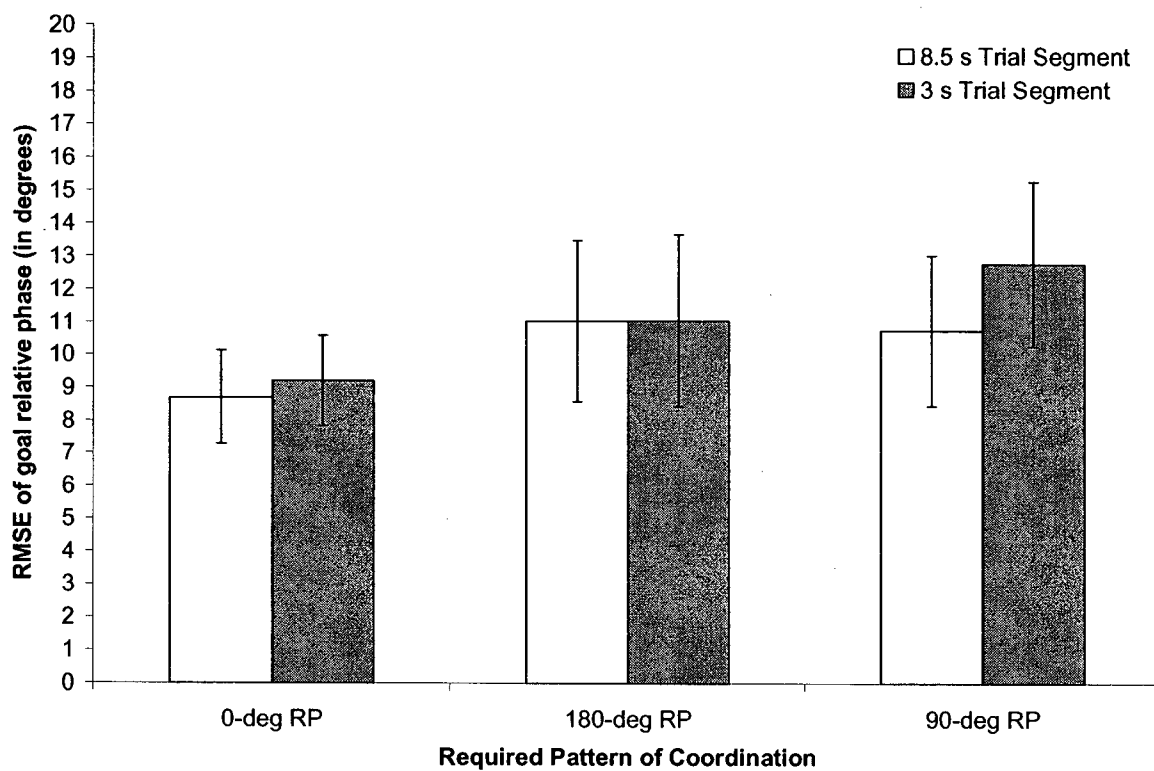
Results

Performance of Bimanual Coordination Patterns

Pattern Accuracy and Stability. The primary measure of performance was the RMSE relative to the respective coordination goal (i.e., 0° , 180°), as well as SD of RP. The 80 trials performed in each coordination mode were divided into 4 blocks of 20 trials. These data were compared to performance on the 90° coordination pattern from the final session of acquisition from each of the participants' respective learning investigation (i.e., from Experiment 1, 2, or 3). The last 80 trials, divided into 4 blocks of 20 trials, were used from Day 10 of learning for comparison purposes. Dependent measures were submitted to a Group (vision, no-vision) x Pattern (0° , 180° , 90°) x Segment (8.5 s, 3 s) x Block (4) analysis of variance (ANOVA), with repeated measures on the last three factors.

Figure 4.2 illustrates RMSE performance for the coordination patterns of in-phase, anti-phase, and 90° RP across all participants for each trial segment. No significant main effect for pattern emerged from the data ($p = .123$). Mean RMSE for the in-phase pattern was 9.0° ($SD = 2.0^\circ$), while mean RMSE for the anti-phase pattern and the 90° pattern were 11.0° ($SD = 3.6^\circ$) and 11.8° ($SD = 4.4^\circ$),

Figure 4.2. RMSE of goal relative phase for pattern (0° , 180° , and 90°) by trial segment (Error bars = SEM).



respectively. Results also revealed no significant main effect for group ($p = .441$) or block ($p = .173$).

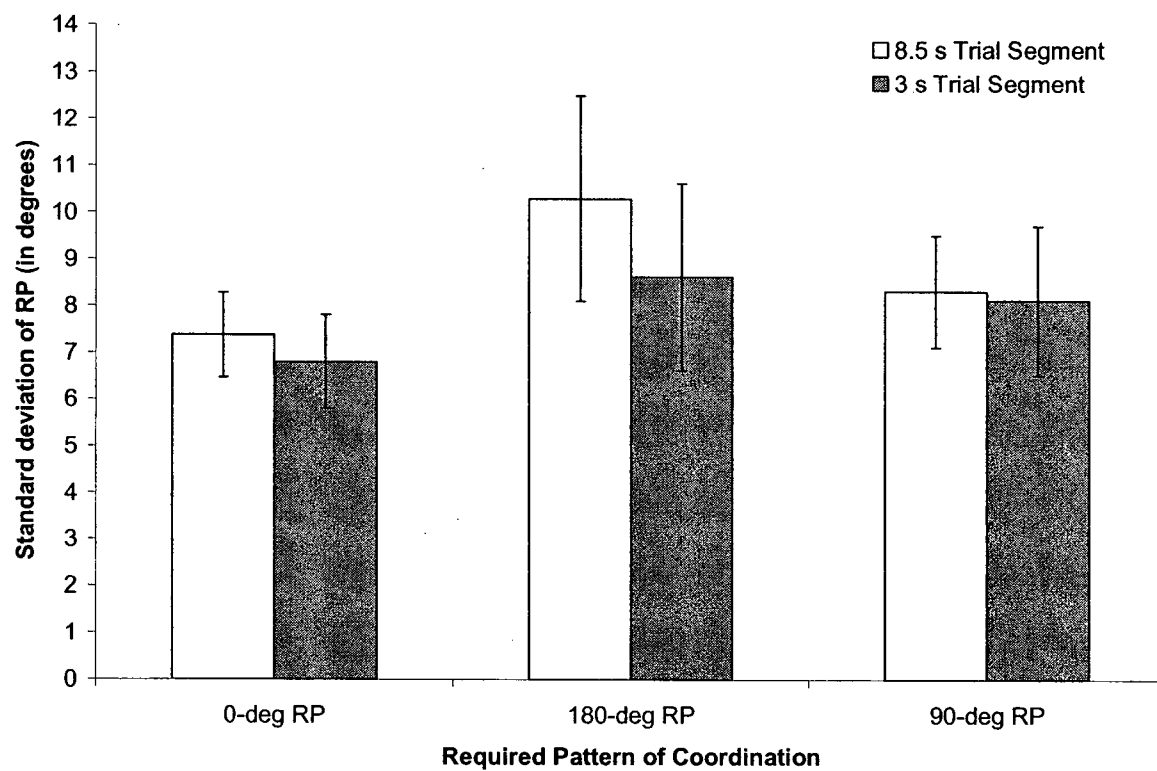
Analysis did reveal a significant group \times segment interaction, $F(1, 8) = 31.08$, $p = .0001$. The vision group displayed lower RMSE values in the 8.5 s segment ($M = 8.8^\circ$; $SD = 2.5^\circ$) versus the final 3 s segment ($M = 11.3^\circ$; $SD = 3.1^\circ$), while a smaller difference emerged between segments for the no-vision group (8.5 s segment: $M = 10.7^\circ$; $SD = 3.8^\circ$; 3 s segment: $M = 11.6^\circ$; $SD = 4.9^\circ$). Taken together, these findings indicate that performance of the 90° pattern is generally more accurate when receiving visual relative motion feedback of the limbs in contrast to performing the criterion task in the absence of a visual information source.

Figure 4.3 illustrates SD of RP performance across all participants for each coordination pattern by trial segment. A main effect for pattern emerged, $F(2, 16) = 4.68$, $p = .025$, whereby in-phase coordination was performed with the greatest stability ($M = 7.1^\circ$; $SD = 1.4^\circ$), followed by 90° RP performance ($M = 8.2^\circ$; $SD = 2.3^\circ$) and anti-phase performance ($M = 9.5^\circ$; $SD = 3.1^\circ$). Post-hoc analysis revealed that in-phase and anti-phase were significantly different from each other. The analysis showed no main effect for group ($p = .421$) or block ($p = .614$).

Findings also revealed a significant group by pattern by segment interaction, $F(1, 8) = 10.63$, $p = .001$. In the 8.5 s trial segment, the no-vision group displayed greater variability in performance of the bimanual coordination patterns ($M = 9.6^\circ$; $SD = 3.1^\circ$) when compared to performance during the final 3 s of the trial ($M = 7.9^\circ$; $SD = 2.8^\circ$) and performance of both segments for the vision group (8.5 s segment: $M = 7.8^\circ$, $SD = 1.9^\circ$; 3 s segment: $M = 7.8^\circ$; $SD = 2.0^\circ$). Performing a large segment of the trial in the absence of a visual information source increased the variability of coordination performance compared to pattern stability when visual feedback was available to monitor on-going movements.

Cycle Frequency. To determine the self-paced cycle frequency for each coordination pattern, an average frequency was determined (in Hz) for each trial. The 80 trials of each coordination mode were then divided into 4 blocks of 20 trials

Figure 4.3. Standard deviation of relative phase (SD of RP) for pattern (0°, 180°, and 90°) by trial segment (Error bars = SEM).



and compared to average cycle frequency of the last 80 trials of the 90° pattern from Day 10 of acquisition for each participant (i.e., Experiment 1, 2, or 3). Cycle frequency for performing 90° RP was also divided into 4 blocks of 20 trials and submitted to a Group (vision, no-vision) x Pattern (0°, 180°, and 90°) x Segment (8.5 s, 3 s) x Block (4) analysis of variance, with repeated measures on the last three factors.

There was a main effect for pattern, $F(2, 12) = 11.55$, $p = .002$, and block, $F(3, 18) = 5.70$, $p = .006$. Post-hoc analysis revealed that cycle frequency for 90° RP was significantly slower ($M = 0.581$ Hz) when compared to natural modes of coordination (0° RP = 0.758 Hz; 180° RP = .745 Hz). Analysis of the main effect for block revealed that block 1 ($M = 0.649$ Hz) was significantly different from blocks 3 ($M = 0.731$ Hz) and 4 ($M = 0.729$). Figure 4.4 further demonstrates that cycle frequency increased across blocks for both in-phase and anti-phase, but remained consistent for 90° RP. Although the block x pattern interaction approached significance ($p = .052$), no other significant main effects or interactions were found.

Probe-RT

The probe data were subjected to a Group (vision, no-vision) x Pattern (0°, 180°, 90°) x Segment (8.5 s, 3 s) x Condition (probe-RT, baseline RT) ANOVA, with repeated measures on the last three factors. Probe-RT for the 3 coordination patterns is illustrated in Figure 4.5. The analysis showed no significant main effect for group ($p = .119$), pattern ($p = .600$), or segment ($p = .160$). However, there was a significant difference between the two conditions, $F(1, 8) = 38.69$, $p = .000$. Attentional costs were exhibited for all three bimanual coordination patterns in the dual-task condition (0° RP = 599 ms; 180° RP = 584 ms; 90° RP = 578 ms), compared to performing the secondary task alone ($M = 442$ ms).

Figure 4.4. Self-paced cycle frequency for pattern (0° , 180° , and 90°) by block (Error bars = SEM).

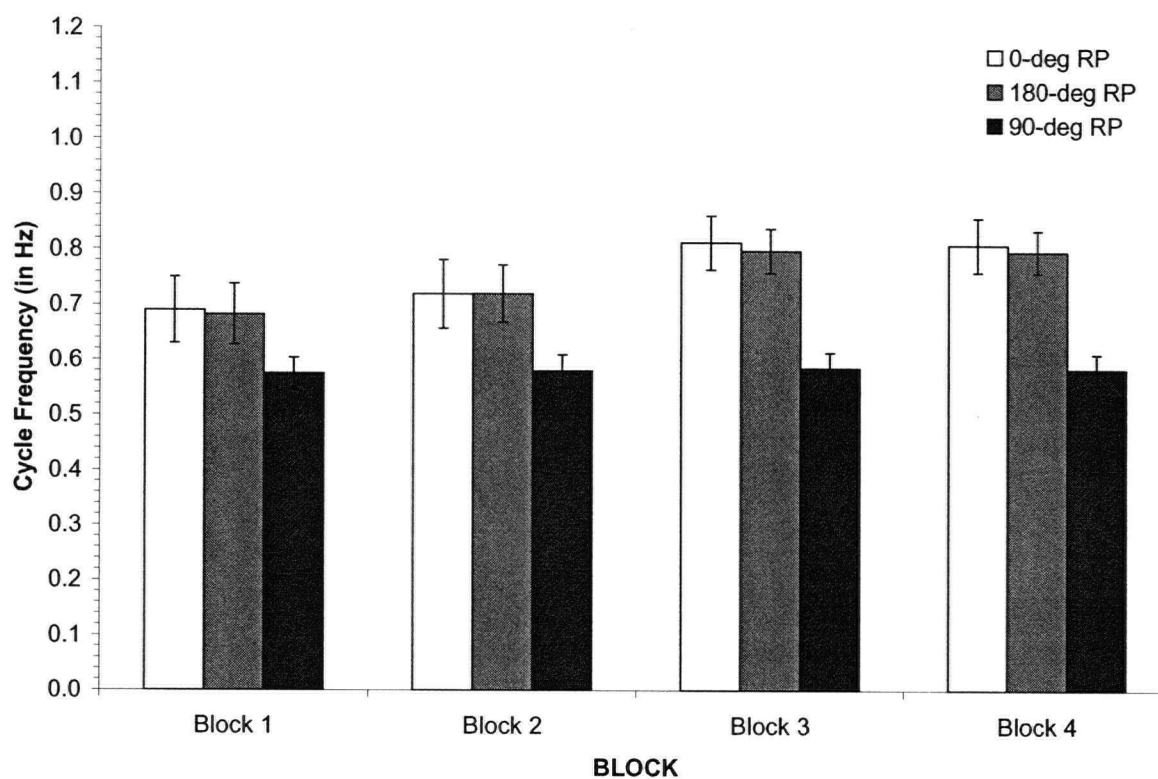
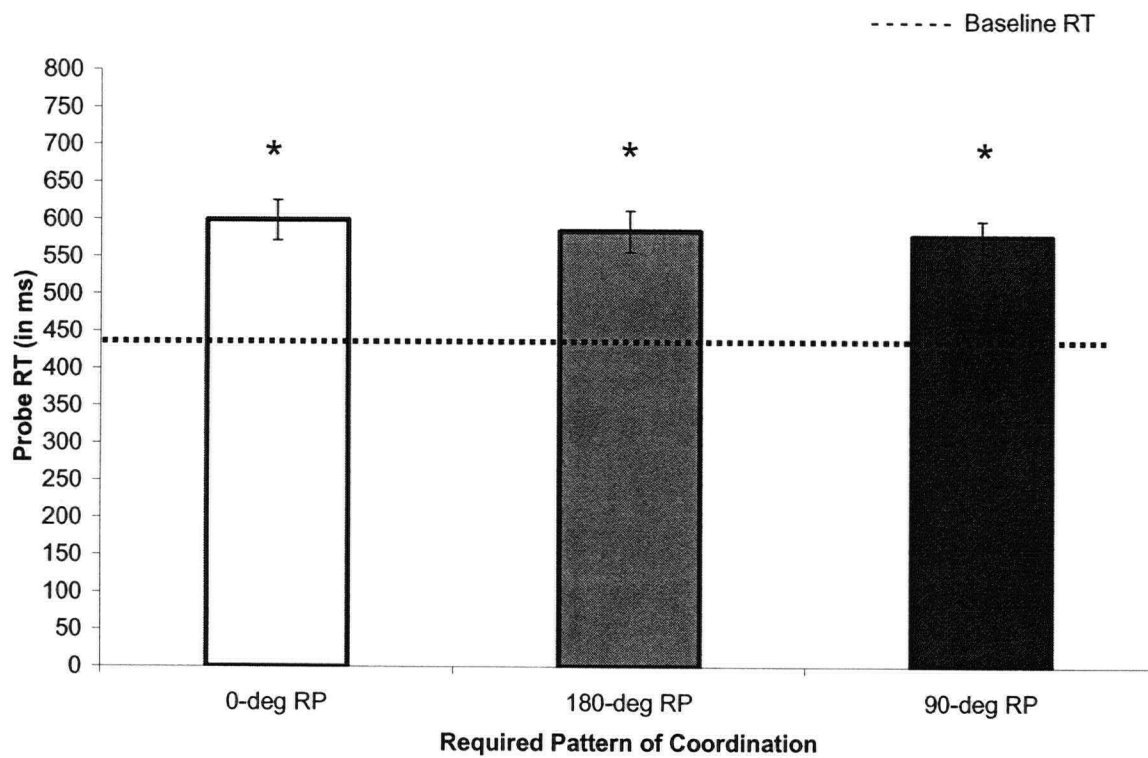


Figure 4.5. Mean probe-RT for 0°, 180°, and 90° of relative phase compared to baseline RT ($M = 442$ ms). An asterisk indicates statistical significance when baseline RT was compared with the corresponding bimanual coordination pattern (Error bars = SEM).



Discussion

The purpose of the present investigation was to evaluate central attentional costs associated with intentional stabilization of a newly learned coordination pattern to bimanual coordination patterns that are naturally stable. This issue was examined by comparing probe-RT between conditions when the secondary task was presented alone versus conditions in which the task was presented in parallel with one of three required bimanual coordination patterns: in-phase, anti-phase, and 90° out-of-phase. In addition, primary task performance of both in-phase and anti-phase coordination modes were compared to performance of the 90° pattern. This was included to evaluate the level of pattern accuracy and stability achieved for the 90° pattern in relation to pre-existing coordination tendencies of the human motor system.

With respect to primary task performance, findings revealed no significant difference between the newly acquired 90° pattern and the inherently stable attractor states of in-phase and anti-phase. Moreover, the lack of a significant difference between coordination patterns appears to be related to movement frequency. When performing each required pattern, participants were permitted to move at a self-selected (or preferred) rate of movement. Findings revealed that the self-paced nature of the task varied depending on whether the individual was performing a newly learned 90° pattern or a pre-existing coordination tendency. More specifically, the 90° pattern was performed at a mean frequency of 0.6 Hz, while in-phase and anti-phase coordination patterns were performed at a mean rate of 0.8 Hz. Clearly, participants adopted a slower speed of movement when performing a newly learned pattern in comparison to pre-existing coordination tendencies. However, an obvious question that arises from the present data is whether stability of the 90° pattern can be maintained in the face of a changing environment. Would our participants, for example, be able to maintain the newly learned pattern at higher cycling frequencies? Furthermore, how would performance at higher cycling frequencies compare to the performance of intrinsic coordination patterns?

First, we predict that differences between in-phase and anti-phase would occur, whereby in-phase coordination would emerge as the more accurate and

stable mode of coordination. This conclusion is based on well-documented evidence, which shows that the anti-phase pattern loses stability and an unavoidable switch from anti-phase to in-phase takes place when movement frequency is progressively scaled beyond a certain critical region (Kelso, 1984). Second, stability of the 90° pattern is also expected to break down at higher movement frequencies. However, instead of a loss of stability to the in-phase pattern, it is expected that a transition to the attractor state of anti-phase would occur. This prediction is based on the evidence of Smethurst and Carson (2001) who have shown that there is a general tendency to switch from 90° relative phase to anti-phase when movement frequency is progressively scaled.

The latter prediction is contrary to the theoretical predictions of Schöner and colleagues (Schöner, 1989; Schöner, Zanone, & Kelso, 1992) who postulated that learning a 90° pattern leads to de-stabilization of the anti-phase pattern because it is the weaker of the two initial attractors (see Zanone & Kelso, 1997). In the present investigation, the anti-phase pattern and the 90° pattern were performed with similar accuracy and stability. Therefore, learning a new coordination pattern in our three previous investigations did not 'annihilate' the anti-phase pattern. Instead, practice of the criterion pattern permitted the learner to break away from pre-existing coordination tendencies, and merely suppress the attraction of the anti-phase mode (also see Shadmehr & Holcomb, 1999). This implies that the anti-phase pattern is still available as an attractor state even when the 90° pattern is being performed. Fontaine, Lee, and Swinnen (1997) and Lee, Swinnen, and Verschueren (1995) have also provided evidence showing that naturally occurring coordination tendencies do not de-stabilize when a new coordination pattern is learned.

In the present study, findings revealed that probe-RT for in-phase and anti-phase were significantly slower than RT at the single-task level. This demonstrates that dual-task interference not only persists for newly learned patterns of coordination (Experiments 1-3), but also exists for coordination tendencies intrinsic to the system. Stated differently, the intentional stabilization of preferred coordination tendencies demands at least a minimal level of cognitive control. Despite the costs associated with increasing coupling strength between the limbs,

intentional stabilization allows for flexibility within the natural dynamics of the system. The effects of intentional processes have now been demonstrated in a number of investigations, which show that people are highly adept at deliberately switching between intrinsic patterns (e.g., Carson, Byblow, & Goodman, 1994; Carson, Goodman, Kelso, & Elliott, 1994; Carson, Byblow, Abernethy, & Summers, 1996; Scholz & Kelso, 1990), as well as in volitionally delaying or inhibiting spontaneous phase transitions from one intrinsic pattern to the other (e.g., Lee, Blandin, & Proteau, 1996). However, in the latter observation, Smethurst and Carson (2003) have recently suggested that the ability to delay the onset of a phase transition needs to be learned.

Within the literature, dual-task interference has also been investigated by assigning different attention priority requirements to the tasks at hand. For example, Temprado et al. (1999) instructed participants to share priority between the required bimanual coordination task and a discrete RT task (non-priority focus condition), as well as give priority to either the intended pattern or the RT task (priority focus conditions). As previously stated, findings showed that pattern variability decreased, while response to the auditory probe increased when assigning attentional priority to the coordination task. However, similar findings were demonstrated, although not to the same extent, when participants were instructed to share their attention (i.e., do your best in each task). According to Temprado et al., this demonstrates the important role of the CNS in spontaneous situations, where the level of stability exhibited by the coordination patterns is not specified in any manner. These results lend support to the notion that dual-task interference persists in tasks that are considered to be preferred tendencies of interlimb coordination.

Investigation of the relationship between attention demands and the coordination of walking has also produced similar findings with respect to dual-task interference. Traditionally, a dominant perspective within the motor control literature has been to view walking as an automatic process given the extensive level of practice this fundamental motor skill receives across the lifespan. Despite the relative ease with which we manage walking, recent evidence suggests that gait control is not an automatic process and requires at least a minimum of cognitive or

attentional involvement for movement control. For example, research has shown an increased attentional cost for walking when compared to standing and sitting (Bardy & Laurent, 1991; Lajoie, Teasdale, Bard, & Fleury, 1993), as well as secondary-task interference to gait control when a concurrent cognitive task is introduced (Evbersbach, Dimitrijevic, & Poewe, 1995). Relative to no-walking baseline measures, Sparrow, Bradshaw, Lamoureux, and Tirosh (2002) have recently demonstrated attentional costs associated with normal (unconstrained) walking and walking in conditions requiring participants to regulate step length on approaching a target. Attentional load was also shown to fluctuate incurring the greatest costs at gait initiation and when an obstacle was encountered, in comparison to RT during steady state or unconstrained walking. Finally, recent evidence has also demonstrated that increased attentional resources are needed for gait control in different populations including the elderly (Brown, Shumway-Cook, & Woollacott, 1999; Marsh & Geel, 2000), as well as persons with Parkinson's (Morris, Iansek, Summers, & Matyas, 2000) and Alzheimer's disease (Camicioli, Howieson, Lehman, & Kaye, 1997). Taken together, these findings indicate that control of gait and control of preferred bimanual coordination states, as shown in the present investigation, are not automatic, but require at least a minimum of cognitive or attentional involvement. When considering that people execute motor skills to achieve a specific goal, it seems counterintuitive that the system would operate independently of central processes.

Interestingly, results of the present investigation showed no significant difference in attention demands between the three coordination patterns. This finding was contrary to our initial predictions, as well as the work of others (Monno et al., 2000; Temprado et al., 1999; Zanone, Temprado, & Monno, 1999; Zanone et al., 2001). When comparing in-phase and anti-phase patterns, a greater performance trade-off (between the coordination pattern and RT task) is typically reported for anti-phase coordination. This has also been found when scaling the frequency of oscillation under different attentional priorities. Manipulating oscillation frequency away from a participant's spontaneous frequency incurs a greater cost at the central

level for anti-phase, in comparison to in-phase, irrespective of attentional focus (i.e., a non-priority focus vs. a priority focus).

Once again, a lack of a differential effect between coordination patterns in the present investigation may be a function of movement frequency. We predict that the attention demands required to sustain anti-phase performance should increase when movement frequency is progressively scaled beyond preferred modes, thereby increasing probe-RT. As cycling frequency increases beyond critical levels, attentional load needed to sustain the pattern should be at its greatest. Similar results are also predicted to occur for the 90° pattern; although it is speculated that reaction time to the probe task will be slower for the 90° pattern in comparison to the anti-phase mode. The 90° out-of phase task is not an inherently stable pattern of the human motor system and phase transitions from 90° of RP to 180° of RP are generally reported when movement frequency is progressively scaled (Smethurst & Carson, 2001).

In essence, phase transitions from anti-phase to in-phase coordination, as well as from performance of the 90° pattern to the anti-phase mode, are predicted to correspond to increases in probe-RT. This idea is based on the findings of Monno et al. (2000) who examined the effects of attentional focus on dynamic stability and phase transitions between coordination states. In this experiment, participants were required to execute an in-phase pattern of coordination while gradually increasing frequency of oscillation under a non-priority and a priority condition. First, findings revealed that phase transitions occurred for both conditions, but were delayed when attentional priority was allocated to the bimanual coordination task. This delay in transition corresponded to an increase in pattern stability. Second, the data revealed longer RT for trials in the priority condition where a phase transition from anti-phase to in-phase occurred. From these findings, Monno et al. maintain that (a) pattern stability incurs a cost at the level of the CNS, and (b) phase transitions may be induced by two different mechanisms. In non-priority shared conditions, transitions may result as a loss of pattern stability, while transitions in a priority focused condition may result from too high of an attentional load needed to sustain the pattern. As such, Monno et al. suggested that central costs associated with

attentional focus may act as a control parameter triggering phase transitions in bimanual coordination. Clearly examining the relationship between cycle frequency, probe-RT, and intentional focus warrants further investigation for understanding the coordination dynamics of preferred tendencies, as well as newly learned bimanual coordination tasks.

Chapter Footnotes

1. Participants recruited from Experiment 3 did not receive feedback from the servo torque motors following trials of in-phase and anti-phase. The torque motors were used in Experiment 3 to facilitate acquisition of the 90° RP task, and therefore, were not required for the purposes of the present experiment.
2. Although no statistical differences were revealed between pre- and post-test RT measures, results did show the p-value approaching significant levels ($p = .064$). Upon visual inspection of the data, it was found that one participant revealed large differences between pre- and post-test measures. For this particular individual, a general increase in RT occurred from pre- to post-test. Prior to in-phase and anti-phase performance, mean RT was 509 ms ($SD = 50$ ms) versus 656 ms ($SD = 120$ ms) following coordination performance. This was an absolute difference of almost 150 ms. One possibility is that RT to the secondary task increased as a result of fatigue, or perhaps, a loss of motivation following 160 trials of in-phase and anti-phase coordination. To demonstrate the impact of this individual on baseline RT, the data were again submitted to a one-way repeated measures ANOVA with the data of this participant excluded from the analysis. Findings showed that the p-value no longer approached statistical significance ($p = .171$). Therefore, an increase in RT from pre- to post-test measures was not a general trend of all participants.

CHAPTER V

EXPERIMENT 5

Removal of Continuous On-Line Visual Feedback Degrades Performance and Increases the Attention Demands of a Bimanual Coordination Pattern

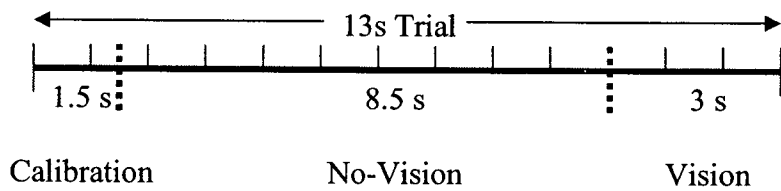
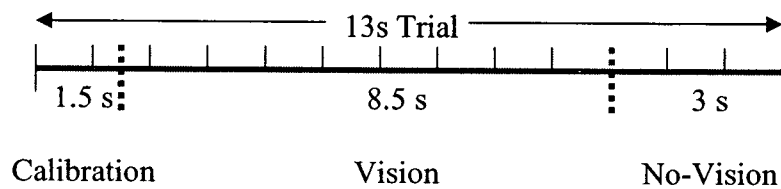
Introduction

In the previous series of investigations, we manipulated the provision of relative motion feedback during performance of the 90° RP pattern. The reason for this manipulation was to determine the relative contribution of continuous on-line visual feedback to the acquisition and performance of a new bimanual coordination task. Findings revealed that changing the availability of visual feedback in the final 3 s of each practice trial influenced coordination performance. Providing continuous relative motion feedback improved the accuracy and stability of the 90° pattern (Experiments 2 and 3), while performance deteriorated when visual feedback was removed (Experiment 1). Results also showed that attention demands increased when the dominant source of feedback was changed in the final segment, irrespective of whether the switch was from a visual source to a proprioceptive source, or vice-versa. What remains unclear, however, is whether the changes observed in coordination performance and attention demands were temporary effects on behaviour, or whether these changes were more permanent in nature. The present investigation was designed to address this issue.

Limitations in Experimental Design: The 'Segment Problem'

In each of the four previous experiments, participants received a 13 s practice trial subdivided into 3 segments of different durations (see Figure 5.1 for a review of the breakdown of trial segments). Segment 1 consisted of the first 1.5 s of the trial. During this time, all participants were provided with relative motion feedback. This permitted individuals an opportunity to appropriately position their limb movements to the criterion template provided on the computer screen. Because this segment was used for calibration purposes, it was not included in analyses of the data. In

Figure 5.1. Breakdown of the 13 s practice trial in Experiments 1 through 4. The top panel represents the trial design used in Experiment 1 and for the Vision group in Experiment 4. The bottom panel illustrates the trial design used in Experiments 2 and 3, as well as for the No-Vision group in Experiment 4.



contrast, we were specifically interested in performance during Segments 2 and 3. The second segment began at the 1.5 s mark and continued for the next 8.5 s, ending 10 s into the trial. At the 10 s mark, the third segment began and continued for 3 more seconds, until an auditory tone signalled the end of the trial. We were able to examine the influence of concurrent visual feedback on the performance of the 90° RP pattern because participants in our various investigations received relative motion feedback for only one of these two segments. More specifically, participants in Experiment 1 only received continuous visual feedback during the 8.5 s segment of the trial, while participants in Experiments 2 and 3 received relative motion feedback for only the last 3 s (not including calibration).

Analysis of the data in Experiment 1 revealed that continuous on-line visual feedback had a critical impact on the acquisition and performance of a 90° RP task. When visual feedback was withdrawn for the last 3 s, many participants were unable to maintain accuracy and stability of the required relative phase pattern. Instead, performance drifted away from the criterion pattern to more intrinsically stable modes of coordination, even after 1, 000 practice trials. This was contrary to our original predictions. Once acquiring the 90° RP task, we expected that individuals would be able to maintain their performance in the absence of feedback, especially considering it was for 3 s only.

Given that participants were exposed to relative motion feedback for a greater portion of time, we suggested that some performers might have developed a control strategy that was dependent on their capability to use the continuous on-line visual feedback to guide on-going movement. When visual feedback was removed in the 3 s segment, these participants were unable to use other information sources to maintain phasing requirements of the criterion task. There are, however, alternative explanations for the findings revealed in Experiment 1.

The original interpretation assumes a relatively permanent change in behaviour when visual feedback is removed for the last few seconds of a trial. However, adding or removing augmented feedback from the environment (while simultaneously performing a complex task) may only act as a perturbation, inducing a temporary disruption in coordination performance. With enough time, the system

may be able to recover to the same levels of pattern accuracy and stability exhibited prior to the perturbation. Considering that (1) the no-vision segment in Experiment 1 was 3 s, and (2) participants only performed 1-1 ½ movement cycles during this segment, the opportunity to recover from the perturbation was not adequately provided.

In Experiments 1-3, findings also revealed that probe-RT was slower in the last 3 s of the trial regardless of whether individuals were performing in the absence or in the presence of continuous on-line visual feedback. Increases in probe-RT indicate a greater attentional cost at the central level. Therefore, in Experiment 1, this cost may be incurred as the individual attempts to maintain a required coordination pattern without the use of visual feedback. When an individual has limited experience or is unable to effectively use information sources other than vision, greater attention demands will be required to optimize performance. As a result, probe-RT increases when relative motion is removed for the final 3 s of the trial. But why might probe-RT increase when visual feedback is provided?

After initial calibration to the computer monitor in Experiments 2 and 3, the individual was unable to check his or her performance until the last 3 s of the trial. Therefore, the vision segment was especially important early in learning given that participants received no specific instructions regarding how to produce the required pattern. Information gleaned during the 3 s vision segment was essential for 'getting an idea of the movement' (Gentile, 1972). Therefore, a central cost was incurred as a result of the increased cognitive effort needed on the part of the learner.

Once again, these interpretations assume a relatively permanent change in behaviour when visual feedback is added or removed from the perceptual display. Adding or removing augmented feedback during a trial may induce only a momentary increase in attention demands. Once an individual adjusts to the new information source, central costs may subsequently decrease. However, considering that the final segment of the trial was 3 s, we could not address whether the central costs observed in our previous investigations were a temporary effect or a more permanent, long-term effect.

In this experiment, participants practiced a bimanual coordination task requiring a phase offset of 90° on two consecutive days, engaging in 100 trials per day. Participants were then required to return to the laboratory for a third session to perform the criterion task under four different feedback conditions. Each test trial lasted a total of 17.5 s, which was subdivided into 3 segments. The first segment was 1.5 s (also referred to as calibration), while the final two segments were equal in length, lasting 8 s each. Relative motion feedback was manipulated in each of the final two segments, whereby participants could receive one of four possible feedback combinations based on whether continuous on-line visual feedback was provided (vision) or removed (no-vision) from the computer screen. Attentional costs were also assessed in each condition using the probe-RT technique.

First, we hypothesized superior performance in the presence of real-time relative motion feedback, while removal of concurrent visual feedback was predicted to permanently degrade performance for as long as visual feedback remained unavailable to direct on-going movement. We also postulated that performance of the 90° pattern would demand attention irrespective of whether visual feedback was available or unavailable in the environment. However, reaction time to the secondary probe was predicted to be slowest immediately following a change in information source (e.g., from a visual information source to a proprioceptive source, or from a proprioceptive source to a visual source).

Method

Participants

Informed consent was received from ten self-professed right-handed individuals from a university population ($n = 5$ females; $n = 5$ males). The mean age of participants was 24.6 years ($SD = 4.1$, range = 19-31 years). None of the participants had prior experience with the bimanual coordination task and all individuals were naïve to the purpose of the experiment. Upon completion of the final session, all participants received remuneration. The experiment was carried out according to the ethical guidelines set by the University Behavioural Science Screening Committee for research involving human participants.

Apparatus

The apparatus was the same as described in Experiment 1.

Primary and Secondary Tasks

Participants were required to learn to coordinate the limbs with a phase offset of 90° RP. While performing the criterion task, participants were required to emit a vocal response as quickly as possible if at any time a computer-generated auditory signal occurred. Both tasks have been previously explained in detail (see Experiment 1).

Procedure

The present experiment consisted of three separate sessions. The first two sessions were held at the same time on consecutive days, while the last session occurred following a 1-day retention interval of no practice. The procedures and general instructions for each session were identical for all participants.

For all bimanual coordination tasks, participants were told that they could move at their own pace, but their overall objective was to make continuous full movement cycles within each acquisition trial that matched as closely as possible to the criterion template displayed on the computer screen (i.e., try not to let the trace vary). The requirement for one movement cycle was explained to consist of the full moving distance between the "IN" and "OUT" markers so that each hand returned to the same starting position.

On phases of the experiment where probe-RT was collected, participants were informed that there was the potential for a computer-generated auditory 'beep' to sound while performing the required bimanual coordination pattern. If the signal for the auditory stimulus occurred, they were instructed to say the word 'pop' as quickly as possible. Instructions also stressed that performance of the coordination pattern should be given maximal priority.

Session 1

Baseline Trials: Probe-RT. Participants were comfortably seated in front of the computer monitor. They were then instructed that they would receive a total of 15 trials. During each trial, reaction time to the auditory probe was collected in the absence of the primary task. These trials served as measures of baseline RT. The auditory probe was delivered at variable times, randomized across trials. Each trial was 13 s in length.

Baseline Trials: Intrinsic Coordination Patterns. Following collection of baseline RT, participants were permitted to place their forearms in the manipulanda and to familiarize themselves with the movement of the apparatus. Criterion templates representing the relative phase patterns of in-phase and anti-phase were then displayed on the monitor. Participants were instructed on how to coordinate the limbs to produce the pattern represented by each template. Following general instructions, participants were provided two practice trials, one at the in-phase pattern and one at the anti-phase pattern. Baseline measures of in- and anti-phase were then collected.

Participants performed a set of 12 trials in which the goal was to flex and extend the limbs in an in-phase mode of coordination, and a set of 12 trials requiring anti-phase coordination. Half of the participants performed the in-phase set first, while the other half received the anti-phase set first. Criterion templates representing in-phase and anti-phase patterns of coordination were displayed on the monitor during the participants' performance. Participants were provided with concurrent visual feedback for the entire trial by orthogonally plotting the displacements of both limbs overlaying the template of the criterion task. All trials were 13 s in duration. For each pattern, auditory probes were presented at variable times on 8 of the 12 trials. Baseline measures of in-phase and anti-phase coordination were collected to assess whether any changes occurred in the dynamic stability of pre-existing behavioural tendencies as a function of practice (see Zanone & Kelso, 1992, 1997).

Practice Trials. The criterion template (i.e., a circle) was now displayed in the middle of the computer monitor. Participants were informed that the goal of the practice trials was to learn how to coordinate the limbs to produce the circle pattern. Participants were told that they could move their limbs with either a right- or left-lead, but after the first ten trials they were required to move the limbs in the same lead-lag relationship for the duration of the experiment. Participants were required to discover the phasing requirements on their own and therefore, received no specific instructions on how to produce the criterion task at any time.

To facilitate acquisition of the 90° criterion task, participants received relative motion feedback (in the form of a Lissajous figure) for the entire 13 s of each trial. Relative motion feedback was superimposed in real-time onto the template of the criterion task and stayed on the screen throughout the trial such that a history plot emerged as the trial progressed. The augmented feedback remained there until the completion of the trial. In contrast to previous investigations (Experiments 1-4), no terminal feedback was provided at the end of the trial. This was due to the fact that participants received concurrent visual feedback for the duration of each trial.

Participants received a total of 100 practice trials, subdivided into 10 blocks of 10 trials. Each participant determined the interval between blocks, in order to offset any potential effects of fatigue across the 100 trials.

Session 2

Practice Trials. Participants performed a total of 100 practice trials in the same manner as described above. No baseline measures of probe-RT or intrinsic coordination patterns were collected on Day 2.

Session 3

Test Trials. Participants were required to perform 90° RP under four different feedback conditions. Trials in each condition lasted 17.5 s and were divided into 3 segments. The first segment lasted 1.5 s, while the final two segments of the trial lasted 8 s each. For the first 1.5 s, participants received relative motion feedback in real-time, irrespective of condition. In the final two segments of the trial, participants

performed 90° RP either in the presence or in the absence of continuous visual feedback (see Table 5.1). In Condition 1, participants received visual feedback for Segment 2 only. For Segment 3, participants were required to perform the criterion task in the absence of feedback (Vision: No-Vision or V-NV). The opposite manipulation occurred in Condition 2. Visual feedback was provided in Segment 3, but not in Segment 2 (No-Vision: Vision or NV-V). In Condition 3, participants received relative motion feedback for the duration of the trial (Vision: Vision or V-V), while visual feedback was removed for the last two segments in Condition 4 (No-Vision: No-Vision or NV-NV). Participants performed 24 trials of each condition, which were presented randomly across 96 trials. To prevent fatigue, the 96 trials were subdivided into 8 blocks of 12 trials.

For each test condition, probes were presented randomly at eight different times. These occurred at: 2.5 s, 4.5 s, 6.5 s, 8.5 s, 10.5 s, 12.5 s, 14.5, and 16.5 s. Probes delivered at the first four times (i.e., 2.5 s to 8.5 s) occurred during the first 8 s segment; while, the last four times (i.e., 10.5 s to 16.5 s) took place during the final 8 s segment of the trial. For the purposes of data analysis, probes at the 2.5 s position and at the 10.5 s position were referred to as Time 1 (T1) because they were the first probes to occur within each segment. Probes at the 4.5 s position and the 12.5 s position were referred to as Time 2 (T2), while probes at 6.5 s and 14.5 s, as well as at 8.5 s and 16.5 s were identified as Time 3 (T3) and Time 4 (T4), respectively. For each condition, a total of 2 probes were presented at each time ($n = 16$ probes/condition).

Baseline Trials: Intrinsic Coordination Patterns. Participants performed 12 trials of the in-phase pattern and 12 trials of the anti-phase pattern in the manner previously described. Once again, auditory probes were presented at variable times on 8 of the 12 trials for each coordination pattern.

Baseline Trials: Probe-RT. Measures of baseline-RT were collected in an identical manner as pre-test measures described earlier.

Table 5.1.

Summary of Feedback Conditions (V = Vision; NV = No-Vision)

Feedback Condition	Condition Abbreviation*	Trial (17.5 s)		
		Segment 1	Segment 2	Segment 3
		1.5 s	8 s	8 s
1	V -NV	V	V	NV
2	NV -V	V	NV	V
3	V-V	V	V	V
4	NV-NV	V	NV	NV

* Determined by the presence or absence of concurrent relative motion feedback in Segments 2 & 3, respectively.

Data Analyses

Statistical analysis was conducted on each of the following dependent measures: RMSE, SD of RP, cycle frequency, and probe-RT. These measures have been discussed previously (see Experiment 1). All post-hoc comparisons were performed using the Tukey HSD procedure ($p \leq .05$).

Results

Baseline RT

To determine baseline RT, a mean reaction time was calculated for pre- and post- acquisition control conditions and submitted to a one-way repeated measures analysis of variance. No significant difference ($p = .190$) was found between pre-acquisition ($M = 393$ ms; $SD = 80$ ms) and post-acquisition ($M = 390$ ms; $SD = 75$ ms) baseline RT. Therefore, baseline RT was calculated using a mean of both pre- and post-acquisition measures ($M = 392$ ms; $SD = 78$ ms).

Intrinsic Coordination Patterns

To assess whether pre-existing coordination patterns were affected by practice on the 90° out-of-phase task, the dependent measures of RMSE, SD of RP, and cycle frequency were submitted to separate 2 x 2 (Pattern x Time) repeated measures ANOVAs. The pattern factor included performance for in-phase and anti-phase, while the time factor included pre-practice and post-practice measures.

Results revealed a significant difference between in-phase and anti-phase for RMSE, $F(1, 9) = 12.05$, $p = .007$, and SD of RP, $F(1, 9) = 15.10$, $p = .004$. The in-phase pattern was performed with less error ($M = 11.2^\circ$, $SD = 3.8^\circ$) and was more stable ($M = 9.6^\circ$, $SD = 3.2^\circ$) in comparison to performance of the anti-phase pattern (RMSE: $M = 16.1^\circ$, $SD = 5.2^\circ$; SD of RP: $M = 15.0^\circ$, $SD = 4.8^\circ$). For RMSE, in-phase coordination was consistent between pre-test ($M = 11.2^\circ$, $SD = 3.9^\circ$) and post-test measures ($M = 11.2^\circ$, $SD = 3.8^\circ$), while anti-phase coordination exhibited a

slight, but non-significant ($p = .085$), decrease in error from the pre-test ($M = 17.9^\circ$, $SD = 5.9^\circ$) to the post-test ($M = 14.3^\circ$, $SD = 4.0^\circ$) (see Figure 5.2, top panel).

For SD of RP, the time factor approached conventional levels of significance ($p = .057$). Post-test performance ($M = 10.9^\circ$, $SD = 3.6^\circ$) tended to be more stable than pre-test performance ($M = 13.5^\circ$, $SD = 5.6^\circ$) for both in-phase (Pre-test: $M = 10.1^\circ$, $SD = 3.7^\circ$; Post-test: $M = 9.1^\circ$, $SD = 2.7^\circ$) and anti-phase (Pre-test: $M = 16.6^\circ$, $SD = 5.2^\circ$; Post-test: $M = 12.7^\circ$, $SD = 3.7^\circ$) coordination (see Figure 5.2, bottom panel). Contrary to the conclusions of Zanone and Kelso (1997), no evidence was found for the destabilization of preferred coordination modes following learning of a new bimanual coordination pattern.

Self-selected rate of cycle frequency increased for in-phase coordination from a pre-acquisition rate of 0.809 Hz to a frequency of 0.972 Hz post-acquisition. Anti-phase coordination also increased in cycle frequency from 0.726 Hz to 0.865 Hz. This was confirmed by a significant main effect for time, $F(1, 9) = 7.14$, $p = .024$. Although preferred rate of cycle frequency tended to be faster for the in-phase pattern when compared to anti-phase coordination, this trend did not reach significance ($p = .085$).

Finally, a Task Condition (probe-RT, baseline RT) x Pattern (in-phase, anti-phase) x Time (pre-test, post-test) repeated measures ANOVA was administered to assess the attention demands of pre-existing coordination patterns. Results showed that probe-RT was significantly slower while performing naturally occurring coordination tendencies, in comparison to baseline RT, $F(1, 9) = 81.64$, $p = .0000$. Analysis revealed no significant differences for pattern ($p = .517$) or time ($p = .687$). Mean probe-RT was 603 ms for the in-phase pattern ($SD = 144$ ms) and 619 ms for the anti-phase pattern ($SD = 169$ ms) (see Figure 5.3).

Practice Trials

By the last block of acquisition on Day 2, all participants were able to produce a relative phase pattern within a $\pm 10^\circ$ bandwidth of the criterion pattern. A representative sample of participant data is displayed for Day 2 as Figure 5.7 in the Chapter Footnotes (see #1).

Figure 5.2. RMSE of goal relative phase (top panel) and SD of RP (bottom panel) for preferred coordination modes (0° and 180°) pre- and post-acquisition (Error bars = SEM).

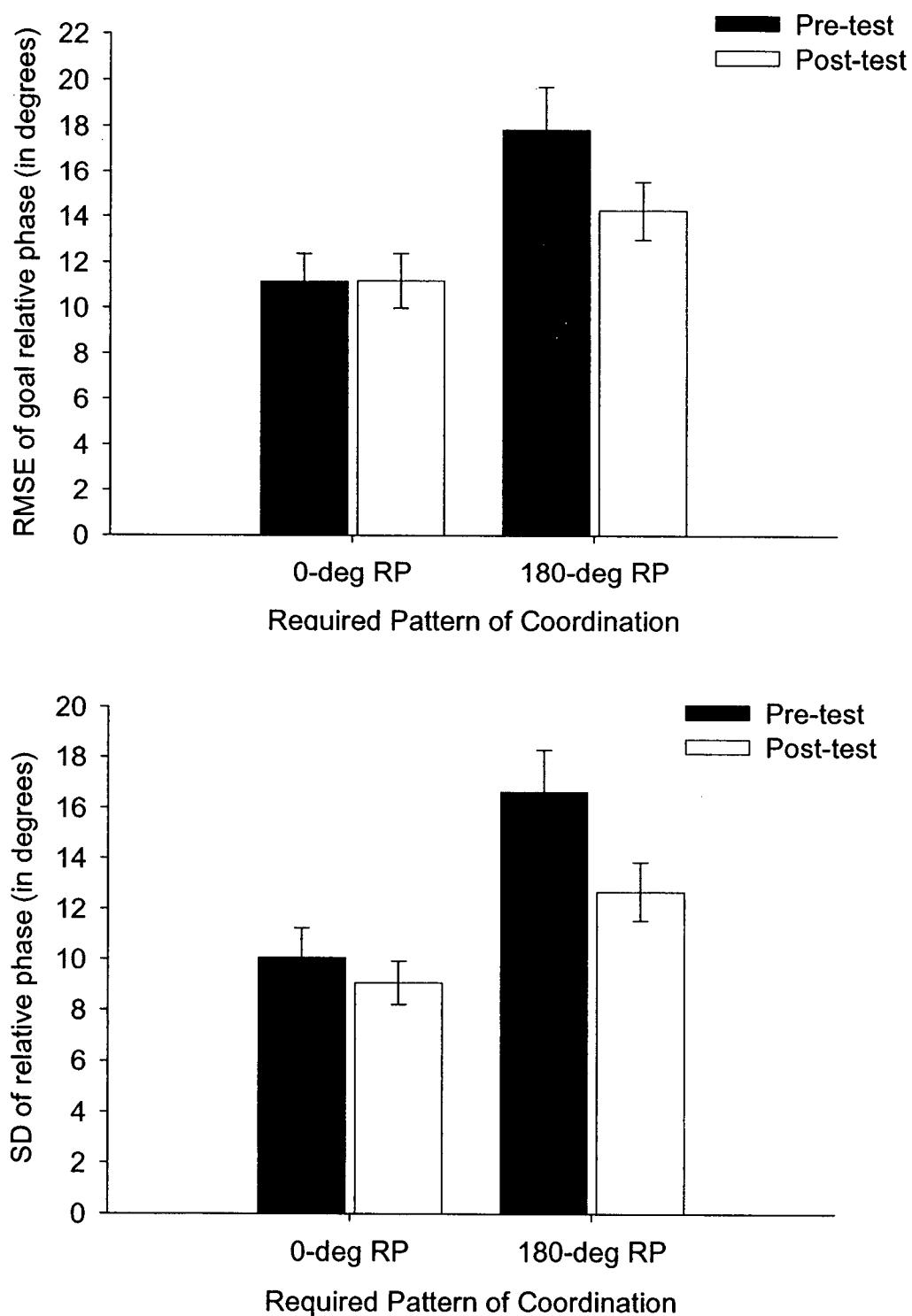
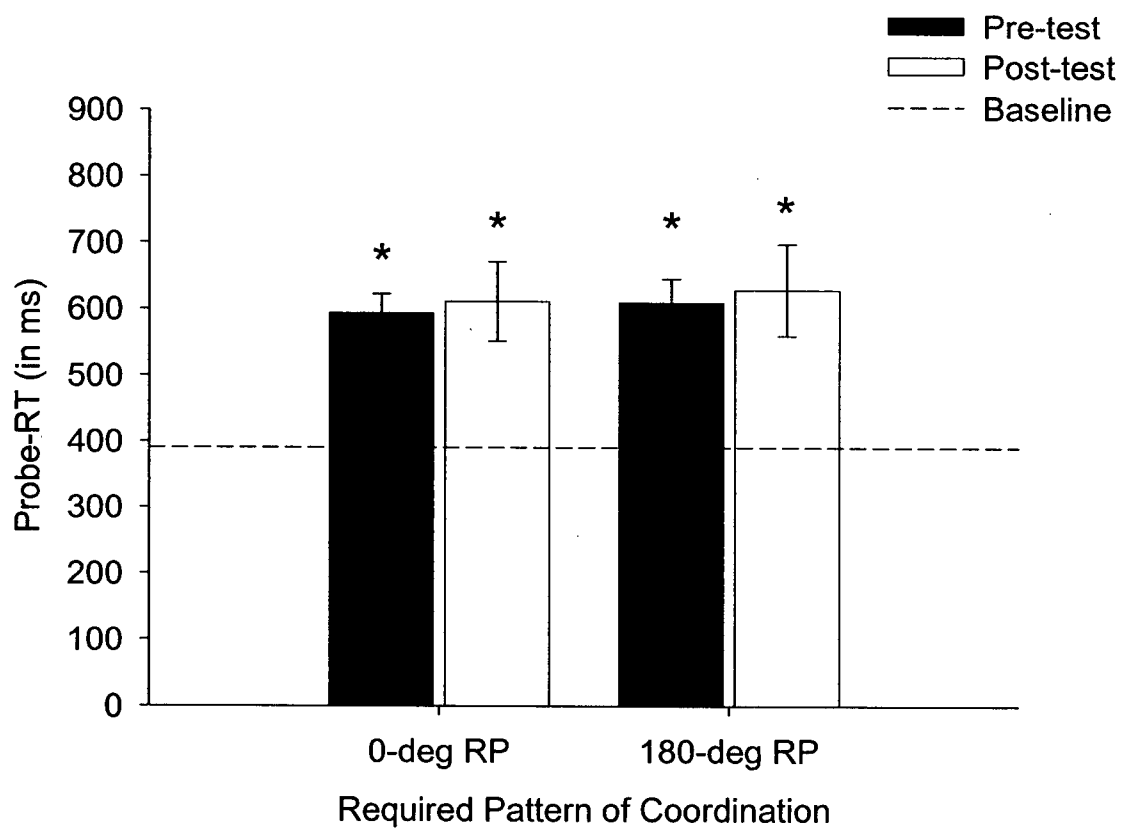


Figure 5.3. Mean probe-RT for 0° and 180° of relative phase compared to baseline RT ($M = 392$ ms). An asterisk indicates a statistically significant difference when baseline RT was compared with the corresponding measure of probe-RT (Error bars = SEM).



Test Trials

Performance of the 90° out-of-phase Pattern. Each dependent measure (RMSE, SD of RP, Cycle Frequency) was submitted to a condition (V-NV, NV-V, V-V, NV-NV) x segment (2) repeated measures ANOVA. No significant differences were found for self-selected cycle frequency. Mean cycle frequency was 0.50 Hz across all conditions and trial segments.

Figure 5.4 displays RMSE in the top panel, while SD of RP is presented in the bottom panel. Analysis revealed a significant condition effect for both RMSE, $F(3, 27) = 12.29$, $p = .0000$, and SD of RP, $F(3, 27) = 13.40$, $p = .0000$. Further post-hoc analysis revealed that the 90° pattern was more stable and performed with significantly less error in the V-V condition (\underline{M} RMSE = 11.4°; \underline{M} SD of RP = 10.5°), as compared with the NV-V condition (\underline{M} RMSE = 25.8°; \underline{M} SD of RP = 14.6°) and the NV-NV condition (\underline{M} RMSE = 30.1°; \underline{M} SD of RP = 16.1°). The goal pattern was also less accurate, as well as more variable, in the NV-NV condition versus the V-NV condition (\underline{M} RMSE = 18.9°; \underline{M} SD of RP = 12.8°).

Results showed a significant condition by segment interaction for both RMSE, $F(3, 27) = 34.84$, $p = .0000$, and SD of RP, $F(3, 27) = 10.04$, $p = .0001$. This analysis revealed that RMSE and SD of RP were significantly lower in the presence of visual feedback. However, when a no-vision segment immediately preceded a vision segment (NV-V) the improvements observed in performance during the vision segment did not reach the levels displayed under vision for both the V-NV and V-V conditions.

Figure 5.5 presents a series of typical relative motion plots obtained for a representative participant on each condition. Panel A represents the V-V condition, while panels B, C, and D correspond to the V-NV, NV-V, and NV-NV conditions, respectively. In panel A it is evident that the individual is coordinating the limbs with a 90° offset for the entire trial. Performance is clearly superior when comparing panel A to the remaining three panels. In Panel B, a circle shape is produced during the vision segment, but a rightward leaning elliptical shape emerges when vision is removed. Following calibration in Panel C, the individual performs one circle shape

Figure 5.4. RMSE of goal relative phase (top panel) and SD of RP (bottom panel) for condition presented by trial segment. An asterisk indicates that a statistically significant difference was found when comparing segments within a respective condition (Error bars = SEM).

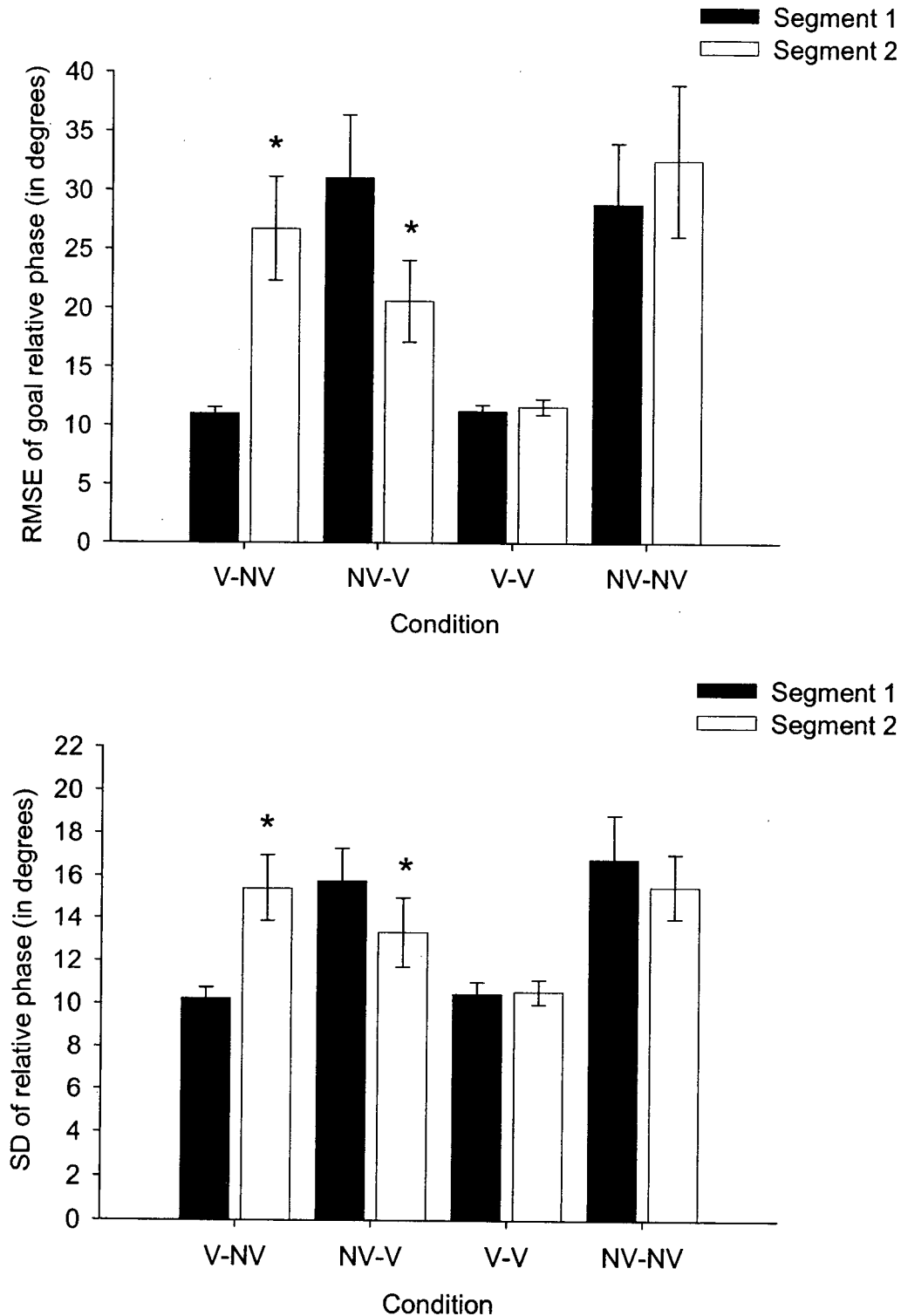
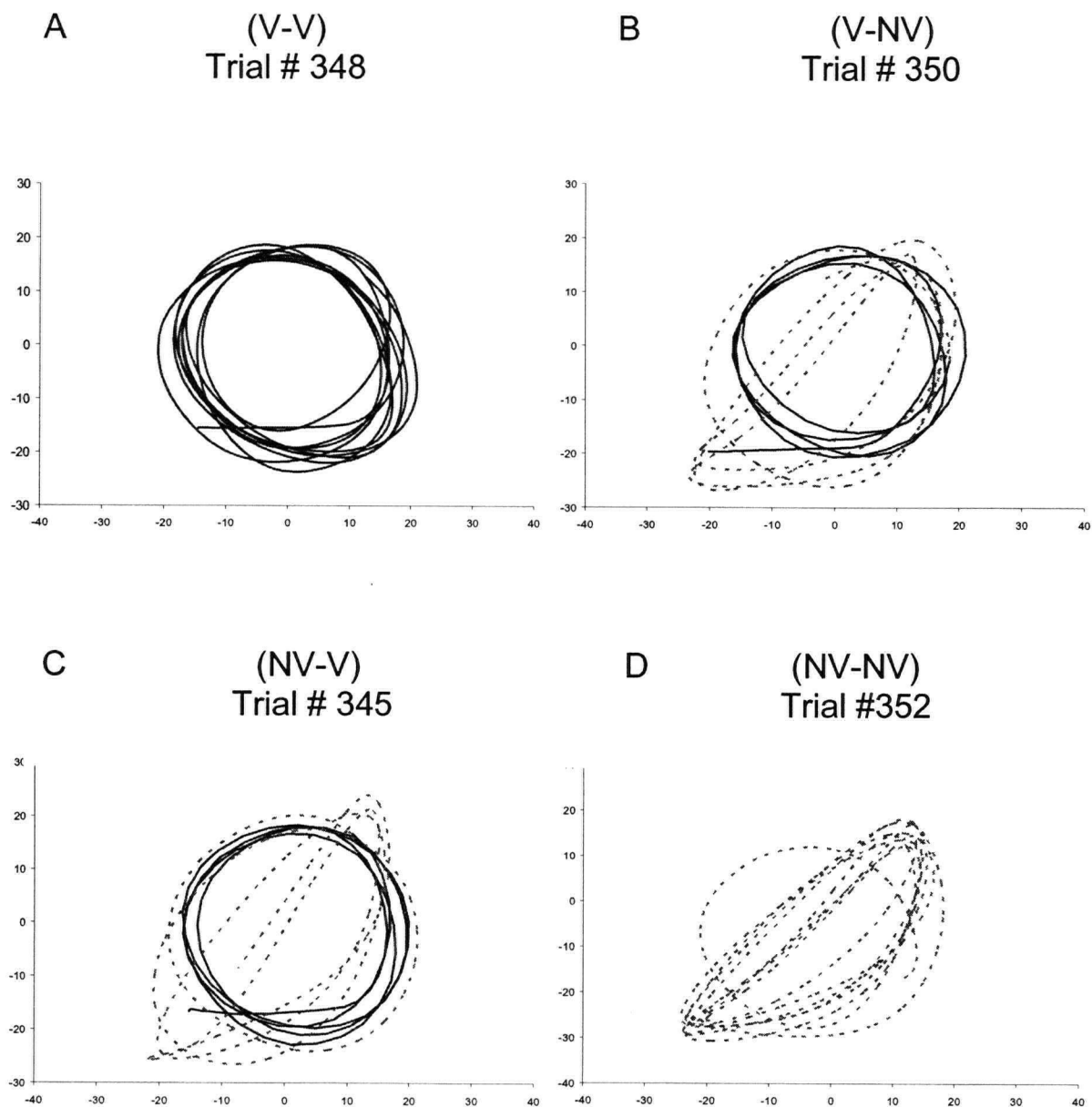


Figure 5.5. Individual trial data displayed as Lissajous figures for Participant 3. Panel A through D represents the V-V, V-NV, NV-V, and NV-NV conditions, respectively. The solid line always represents a vision segment, while the dotted line always represents a no-vision segment (x-axis = right forearm displacement, y-axis = left forearm displacement).

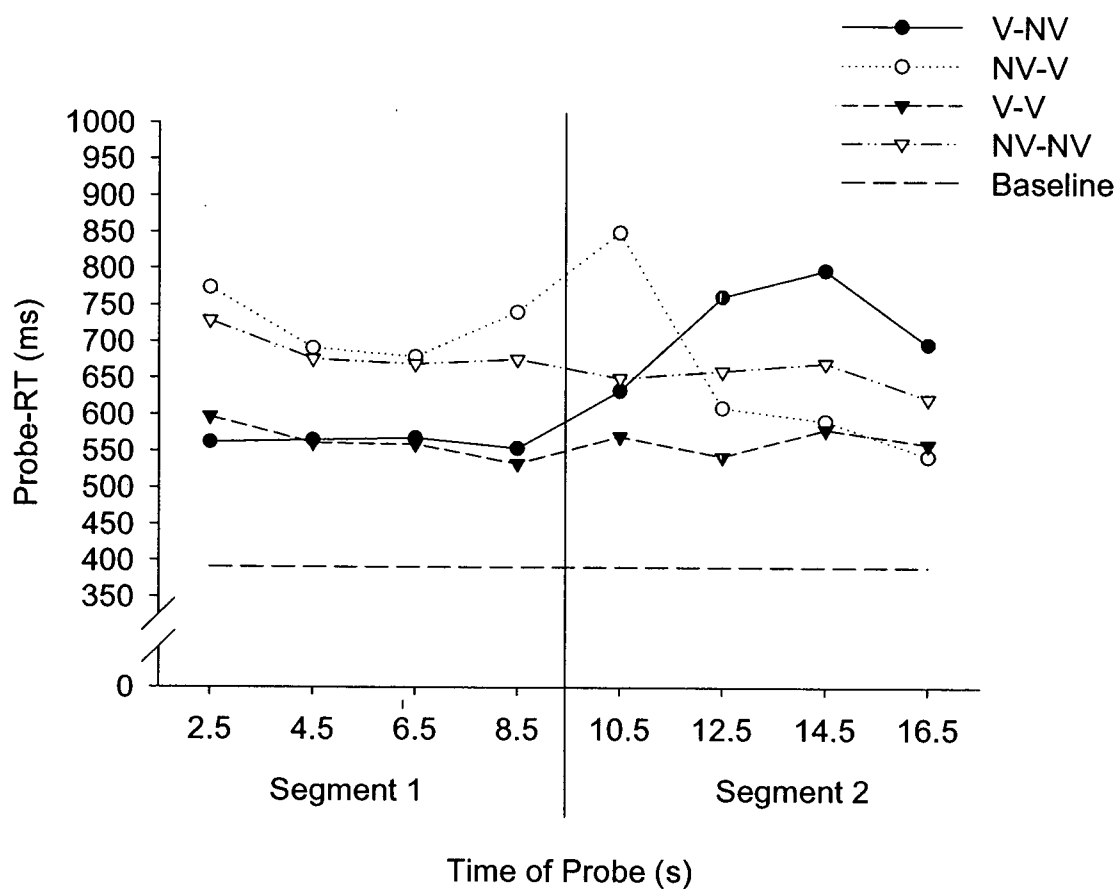


and then drifts towards in-phase. Performance is maintained at this preferred phasing tendency until vision is restored, whereupon the individual immediately returns to a phase offset of 90°. Panel D, displays a similar finding. Following calibration, the learner makes one circle shape and drifts away from the criterion pattern towards in-phase. However, this is maintained for the rest of the trial because feedback was not restored to the computer monitor. This series of Lissajous figures clearly demonstrates a permanent phase drift towards a more preferred coordination tendency whenever visual feedback is removed from the perceptual display. Most importantly, performance does not return to the same levels of accuracy and stability exhibited prior to removal of the feedback even when time is provided to recover from the perturbation.

Probe-RT. A preliminary analysis was first conducted to verify that performance of the 90° pattern was maintained on trials where a probe occurred, in comparison to no-probe trials (see Experiment 1 for further discussion of rationale). RMSE data were submitted to a Trial Type (probe, no-probe) x Condition (V-NV, NV-V, V-V, NV-NV) x Segment (2) repeated measures ANOVA. No significant differences were found for trial type ($p = .284$). Mean RMSE was 21.5° when an auditory probe was administered while performing the 90° pattern and 22.0° in no-probe trials. The probe data were then submitted to a 4 x 2 x 4 x 2 (Condition x Segment x Probe Time x Reaction Time) repeated measures ANOVA. Probe time referred to the position of a probe within a trial segment: T1 (2.5 s, 10.5 s), T2 (4.5 s, 12.5 s), T3 (6.5 s, 14.5 s), or T4 (8.5 s, 16.5 s); while the factor of reaction time included the measures of probe-RT and baseline RT.

Findings revealed a significant four-way interaction, $F(9, 81) = 2.23$, $p = .024$, for all factors. Mean probe-RT for each condition is displayed as a function of segment and probe position in Figure 5.6. The analysis revealed that probe-RT was consistently faster in the presence of visual feedback, as compared to all no-vision segments. Importantly, when visual feedback was followed by no-vision (V-NV), RT to the secondary probe increased markedly. In comparison, when a no-vision

Figure 5.6. Mean probe-RT plotted as a function of segment and probe position for each condition compared with baseline RT ($M = 391$ ms)*.



*Note: Error bars are not presented above to enhance visual presentation of the four-way interaction. Instead the same data is displayed with error bars in Figure 5.8, which is provided in the Chapter Footnotes (see #2). In Figure 5.8, the V-NV and NV-V conditions are displayed separately from the V-V and NV-NV conditions.

segment was followed by visual feedback (NV-V) there was a spike in probe-RT (immediately after the transition to visual feedback) followed by a rapid decline in probe-RT to levels observed in the vision segment of the V-NV and V-V conditions. These data support the idea that attention demands increase when a switch from visual to proprioceptive feedback sources occurs within a trial. Moreover, the central costs associated with these changes appear to be relatively persistent in nature. In contrast, shifting from a proprioceptive information source to a visual source induces only a temporary increase in attention requirements. Following the switch, it appears individuals quickly adjust to the provision of continuous on-line visual feedback, and central costs subsequently decrease to pre-transition levels.

Irrespective of whether visual feedback was available or unavailable to guide on-going movement, post-hoc analysis revealed that probe-RT was always significantly slower when performing the required pattern, as compared to baseline RT. This provides support for our previous findings (Experiments 1-4), which suggest that the execution of the 90° pattern is attention demanding. Central costs were significantly less in the V-V condition ($M = 563$ ms) when compared to all other conditions (V-NV = 642 ms; NV-V = 685 ms; NV-NV = 669 ms).

Discussion

In the present experiment, four different feedback conditions were examined based on whether concurrent visual feedback was available or unavailable to guide performance in one of two trial segments. We predicted superior performance of the 90° pattern in the presence of continuous visual feedback, while removal of visual feedback was hypothesized to permanently degrade performance for as long as the information source was unavailable to guide on-going movement. Our findings confirmed this prediction. The 90° pattern was more accurate in the presence of concurrent visual feedback. Importantly, these data also show that when visual feedback is removed from the perceptual display, a relatively permanent phase drift occurs towards a more preferred coordination tendency. That is, performance does not return to the same levels of accuracy and stability exhibited prior to removal of the feedback even when time is provided to recover from the environmental

disruption. These findings indicate that the 3 s segment in Experiment 1 was representative of coordination performance under conditions of no-vision. The data confirms that when vision is removed as an information source (while executing the 90° pattern) individuals are generally less effective at suppressing the influence of pre-practice coordination tendencies to maintain the phasing requirements of the required task.

When a no-vision segment immediately preceded a vision segment, findings showed that the difference between segments was not as pronounced in comparison to the V-NV condition, nor did performance during the vision segment reach levels comparable with performance in the V-V condition. The former observation is also consistent with our previous results (Experiments 2 and 3). These data indicate that concurrent visual feedback is less effective for inhibiting the influence of pre-existing coordination biases if it is presented after the limbs are already moving. When vision is restored the individual attempts to correct the movement, but appears to experience difficulty in overcoming the physical properties of a moving limb (e.g., inertia) or in reducing the already-established coupling strength between the limbs. As a result, performance gains are not as large in comparison to performance when vision is presented first. It is even possible that the performer would experience greater performance benefits by stopping the movement and beginning the pattern over again. Of course, this was not an option given the procedures of the current experiment.

With respect to probe-RT, we predicted performance of the 90° pattern would demand attention irrespective of whether visual feedback was available or unavailable in the environment. This prediction was also supported. Our data revealed that performance of the 90° pattern was attention demanding under all four feedback conditions. Interestingly, probe-RT dramatically increased in the V-NV condition directly following the switch between information sources. However, this increase was only temporary as probe-RT immediately returned to levels comparable with the V-V condition. This finding indicates that presenting visual feedback during a trial will momentarily increase attentional load. Once the individual adjusts to this new information source, central costs will subsequently decrease. For

example, when relative motion displacement plots are provided in the middle of a trial, individuals are suddenly required to make spatial (or visuomotor) transformations that relate limb movements made in the horizontal plane to information captured in a single percept (i.e., a circle) on a vertical screen. It is possible that spatial transformations require additional attention (Puttemans, Vangheluwe, Wenderoth, & Swinnen, 2004) until the individual can adapt to the feedback source.

An increase in probe-RT following a switch from proprioceptive feedback to visual feedback is consistent with the findings of both Experiments 2 and 3 where probe-RT during the vision segment was significantly slower in comparison to probe-RT in the absence of vision. However, the present findings also show that providing a longer final segment in Experiments 2 and 3 would have enhanced our interpretation of the data. Given a longer final segment, we would have likely seen only temporary increases in probe-RT.

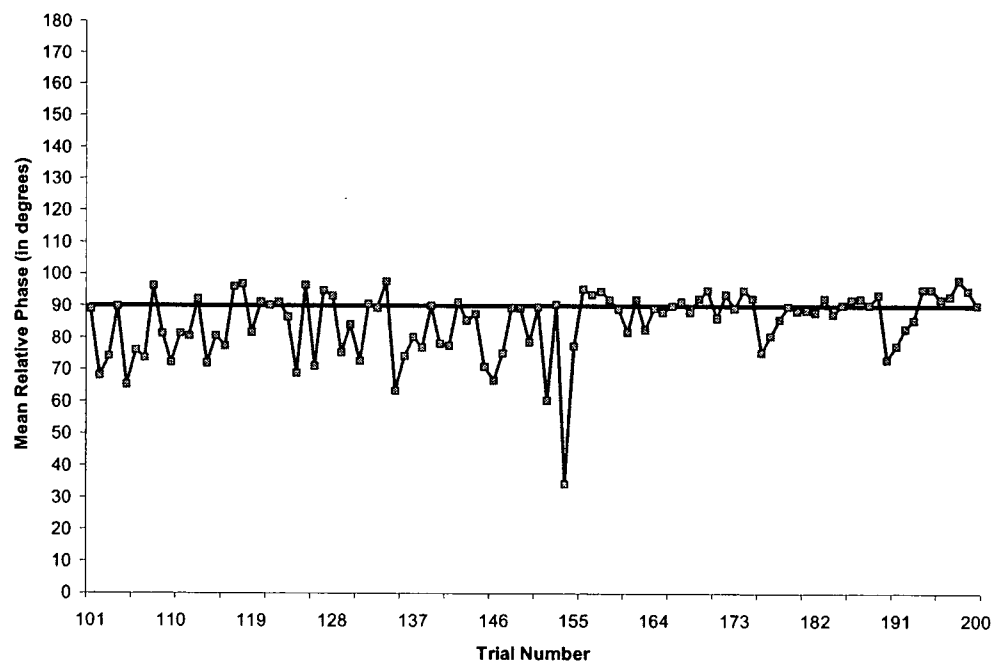
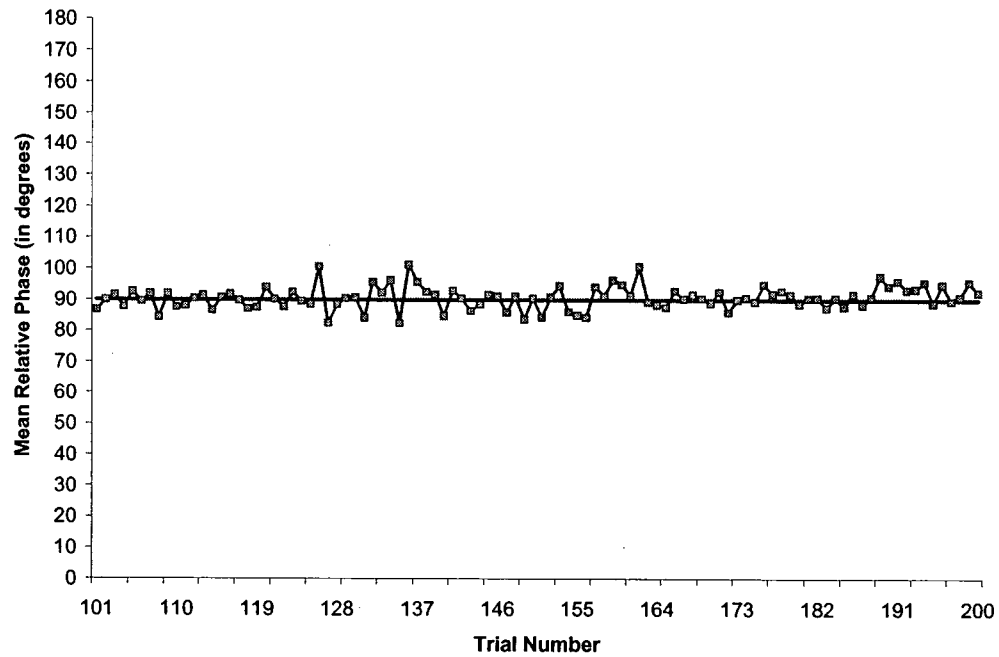
The findings of the present investigation suggest that performing the 90° pattern in the presence of augmented visual feedback is less attention demanding than performing in its absence. One possible reason for this decrease in central costs is that concurrent visual feedback (in the form of a Lissajous trace) is relatively simple, clearly specifies the task goal, and provides performers with crucial features of the movement, which alert the individual to the properties and relationships inherent within the task. In essence, real-time relative motion displacement plots provide the individual with information that they do not necessarily have to find on their own, thereby reducing cognitive load. This idea also follows when providing a criterion template, as well as Lissajous traces of performance superimposed onto the template. In this respect, participants are provided very salient information regarding performance, which reduces the cognitive effort required to detect that an error has occurred.

Explanations for differences in attention demands between vision and no-vision feedback conditions may also have neural origins. For example, Debaere, Wenderoth, Sunaert, van Hecke, and Swinnen (2003) have recently provided evidence for a relative functional dissociation between several regions of the brain

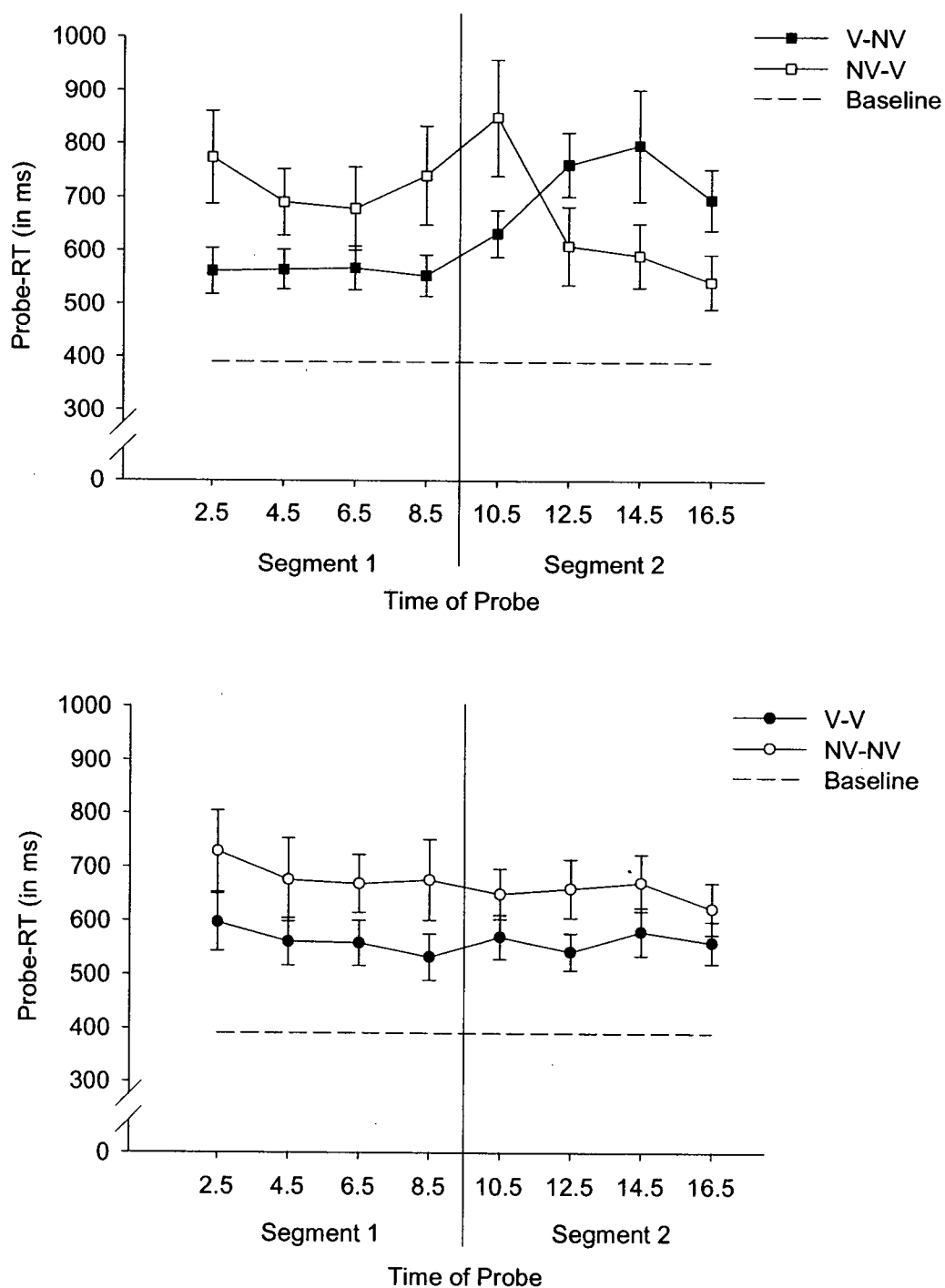
when examining cyclical bimanual coordination movements in the presence or in the absence of continuous on-line visual feedback. In this investigation, participants were required to perform a newly learned 90° pattern under externally guided or internally guided conditions. In the former condition, on-line feedback was provided in the form of a Lissajous figure. In the latter, participants were required to close their eyes and produce the movement on the basis of a memory representation, without on-line visual feedback. Using functional magnetic resonance imaging (fMRI), results showed higher activation levels under externally guided coordination in the inferior temporal gyrus, the superior parietal cortex, the premotor cortex, the thalamus, and the cerebellum (lobule VI). In contrast, preferential involvement of the basal ganglia, the supplementary motor area, cingulate motor cortex, the inferior parietal, frontal operculum, and cerebellar lobule IV-V/dendate were shown during internally-guided coordination. The idea that performance discrepancies in the present investigation may be a result of the activation of differential pathways in the central nervous system is an important one. It may help explain the role of various brain regions, and the efficiency with which each processes information for the control and guidance of bimanual coordination movements. This has obvious implications for motor disordered groups in a rehabilitation setting. For example, providing Parkinson's patients with continuous visual feedback may facilitate acquisition of new bimanual coordination patterns. In a motor disorder like Parkinson's disease the basal ganglia is a deficient brain area, which results in disruption of internal generation of movement. However, since real-time relative motion feedback provokes higher levels of activation in the parietal-premotor area of the brain, bimanual coordination performance is predicted to improve because the basal ganglia can be largely bypassed. From this perspective, investigating the benefits of augmented feedback is clearly warranted for clinical applications in various populations, including motor disordered groups, as well as older adults (see discussion of Experiment 2).

Chapter Footnotes

- 1 Figure 5.7. Individual trial data for Participants 1 (top panel) and 9 (bottom panel). Mean RP is plotted across 100 trials for Day 2 of practice.



- 2 **Figure 5.8.** Mean probe-RT compared with baseline RT ($M = 391$ ms) for the V-NV and NV-V conditions (top panel) and the V-V and NV-NV conditions (bottom panel) plotted as a function of segment and probe position (Error bars = SEM).



CHAPTER VI

Attention Demands across Extended Practice of a Bimanual Coordination Task: General Discussion

Man's versatility in developing skills required to cope with modern living is extremely great. Depending on where he lives in the world, he will acquire one or more of the thousands of different languages and dialects. Depending on the kind of work he undertakes, he will develop hundreds of technical skills. Entirely without being aware of it, he will develop countless universal skills ranging from those required for standing up, sitting, walking, running and manipulating objects to those required in perceiving the world about him. Yet in spite of this tremendous versatility, man's capacity is not limitless. The rate at which he acquires skills and the level of performance he is able to attain are subject to limitations imposed by his musculature, his nervous system, and the characteristics of the activities themselves (Fitts & Posner, 1967, p. 1).

When observing everyday behaviour, it becomes readily apparent that human motor performance is not constrained to the execution of only one task at a time. Rather, individuals often display the capacity to effectively perform two tasks concurrently (e.g., walking and talking at the same time). However, the simultaneous execution of two tasks can also be very difficult, and performance is rarely of the same quality than if each task had been performed alone. Referred to as dual-task interference, the primary purpose of this thesis was to investigate the performance of dual-tasks and observe how attentional limitations in performance change across the time course of motor learning.

Specifically, we investigated the attention demands of three bimanual coordination patterns (0° , 180° , and 90° of relative phase) across a series of five experiments. The bimanual coordination tasks were chosen because they are more representative of real-world activities (Hodges & Lee, 1999), when compared to traditional tasks normally employed in the laboratory setting. Furthermore, this approach allowed us to compare the attention demands of pre-existing coordination tendencies (i.e., 0° RP, 180° RP) with the attention demands of a relatively difficult pattern (i.e., 90° RP) that cannot generally be performed prior to practice. Within a controlled setting, however, this pattern can be acquired in a relatively short period

of time versus the acquisition of sport skills in general. Providing practice sessions for the learning of the 90° pattern allowed us to investigate changes in attention demands as a function of practice via a dual-task paradigm.

Results showed that RT to a discrete secondary probe decreased as a function of practice, but never reached automatic levels (as defined by modal perspectives of attention) even after 200 (Experiment 5) and 1, 000 (Experiments 1-3) trials of task-specific practice. These findings suggest that skilled performance is not impervious to dual-task decrements; rather performers in the advanced stages of learning merely show less decrement than in earlier stages. This interpretation was further strengthened by the finding that intrinsic bimanual coordination patterns did not appear to operate automatically. In Experiment 4, dual-task decrements were demonstrated for both in-phase and anti-phase modes of coordination indicating that voluntary stabilization of even preferred coordination modes require at least a minimal amount of cognitive or attentional involvement.

Findings of this nature have important practical applications for the concomitant execution of many everyday tasks. One such example is the use of cell phones while driving. Research using car simulators and laboratory-based simulated driving situations provide evidence that demonstrates an attention-related basis for driving accidents. For instance, Strayer & Johnson (2001) reported that drivers talking on a cell phone miss 2 x more simulated traffic signals when compared to driving without talking on a cell phone. More importantly, when signals were identified and reported, RT was significantly slower as compared to RT when only performing the task of driving. The results of our experiments would further suggest that attention-based deficits in performance will continue to persist even if the individual is well-practiced at the two tasks, further highlighting the dangerousness of cell phone use while driving.

Attention Demands: Theoretical Perspectives

From a theoretical perspective, our findings do not support traditional modal views of automatic processing, which postulate that performance on a task will eventually become automatic (i.e., attention-free processing) as a function of

practice. From a practical perspective, it seems highly unlikely that humans would ever reach this level of processing given the complex nature of even the simplest of human movements. This is obvious in that research has shown that practice does not necessarily make perfect. For example, Crossman (1959) reported small performance improvements in the task of cigar-rolling by workers who made over 10 million cigars and possessed seven years of task experience. This is an important idea as dual-task interference may always persist as long as learning takes place and motor performance continues to improve (Blischke, 1998). Even Fitts (1962), who labeled his final stage of learning with the term 'autonomous', recognized that new learning occurs at this final stage albeit at a decreased rate. Rather than true performance plateaus or limits in the individual's capacity for improvement, Fitts suggested that physiological aging and/or a loss of motivation are the real determinants of an individual's failure for perpetual gains in performance. As long as learning takes place, performance will be attention-demanding.

In contrast to the original controlled and automatic theory of Schneider and Shiffrin (1977, *see Appendix A*), more recent discussions on attention tend to focus on the qualitative changes that occur in task structure (e.g., strategy changes – Cheng, 1985), the performance of individual task components (e.g., strengthening – Anderson, 1982), or the performance of component sequences (e.g., composition – Anderson, 1982). For example, Vallacher & Wegner (1987) suggest that attention to a task is devoted to one of many different levels of organization. In general, people attend to the highest level of organization possible, which allows the task to be completed without shifting to lower levels of attention. In this sense, the lower levels of organization are automatic, but attention is not withdrawn, merely shifted to a higher level of organization, which becomes progressively higher with more practice. In certain environmental conditions, however, attention may be forced down to a lower level. Logan (1992) provides an example to illustrate this idea by describing different attention levels associated with dialing a telephone number. When dialing we tend to think of the number we are dialing, not the buttons we are pressing. However, if one of the buttons was to stick, our focus of attention would shift to pressing the button. From this perspective, attention is always required for goal-

directed movement; however, the way in which the individual attends may change as a function of skill level.

Cheng (1985) suggests that improvement in performance results from optimizing strategies and the restructuring of the task components. This idea becomes apparent when an individual is asked to find the sum of ten 5s. To derive a solution to the problem, alternative methods may be used. The individual may perform ten addition operations to derive the answer or may solve the problem in only one operation by using the multiplication table. However, use of either method is dependent on the skill level of the performer. An individual who is just learning mathematics (i.e., a beginner or novice), will not know the multiplication table. Therefore, the person will have to perform ten addition operations. It is only later in learning, when the individual knows the multiplication table, the same problem can be solved in only one step. Such gains in efficiency are not a result of the individual performing the addition operations in a capacity-free mode of processing. Instead, restructuring the task components and using a more efficient procedure achieved the gains. What changed was how the information was processed, not what information was processed.

According to Haider and Frensch (1996), decreases in RT observed using the dual-task paradigm, may also reflect a reduction in amount of information being processed, and not necessarily a reduction in attention demands. This idea is based on the observation that skilled performers learn to discriminate between task-relevant and task redundant information. This is advantageous to the performer because it reduces the amount of information to be processed to only the relevant aspects of the task. Therefore, information processed at early stages of acquisition may be qualitatively different than information that is processed at advanced stages. From this perspective, what changed was the information, not necessarily how the information was processed.

In recent years, attention demands (in relation to automaticity) have been discussed most often from either a procedural account or a memory account of skill acquisition. A procedural account proposes that procedures are developed then refined and strengthened as a result of practice. In contrast, memory accounts

suggest that performance is dependent on memory retrieval (rather than resource limitations), which becomes faster and more efficient as a function of practice. Procedural accounts of skill acquisition generally refer to Anderson's Framework for Cognitive Skill Acquisition, while memory accounts reference Logan's (1988) Instance Theory of Automaticity, the latter of which, will be presented first.

Logan's (1988) Instance Theory of Automaticity

According to Instance Theory, the novice performer initially performs many tasks by following a mental algorithm that is general in nature. Eventually, this same task is solved by a single-step direct-access retrieval of the solutions from long-term memory. For example, when an adult is asked to report the sum of 9 plus 6, they can provide a response rather fast and effortlessly. For a child, calculating the sum of 9 plus 6 is arduous and slow. To explain this, Logan proposes that a 'memory trace' (i.e., instance) is left in long-term memory each time the individual solves the problem. The next time the individual performs the task, associated traces are activated, and a new trace is laid down. Furthermore, Logan maintains that the individual may respond with either solution, but it is generally a race between computational processes (i.e., the algorithm known to solve the problem) and memory processes (i.e., retrieval of an appropriate memory trace). Early in learning, the computational processes are faster. With practice, however, the memory trace becomes stronger and eventually the likelihood that an appropriate trace can be retrieved before the algorithm is finished increases. Accordingly, processing at later stages of learning does not imply processing without attention; rather, processing involves a different way of attending relative to early stages of acquisition.

Anderson's (1982) Cognitive Framework of Skill Acquisition

Following Fitts and Posner's (1967, see *Appendix A*) phase approach to the acquisition of skill, Anderson (1982) developed a framework, which takes into consideration the underlying mechanisms of performance throughout each phase of acquisition, as well as the transition that occurs between one primary stage and another. In general terms, Anderson's theory is based on the notion of a production

system in which a distinction between declarative and procedural knowledge is fundamental.

In the first stage, referred to as the declarative knowledge phase, it is postulated that the learner receives instruction and information regarding the to-be-learned skill or task. This information is then encoded by the learner as a set of facts, which are used by general procedures already possessed by the individual in order to generate behaviour. Rehearsal is crucial at this stage because the facts must be retained in working memory so that they are available for use. Activities that occur within this stage of development are analogous to the activities described in Fitts' cognitive stage (see Appendix A), and essentially involve the acquisition of explicit knowledge in the form of declarative rules pertaining to a specific domain.

As practice continues, specific procedures develop so that the goals of the task are more readily achieved. This process involves the conversion of knowledge from declarative form into procedural form. This process can be described as the acquisition of production rules that associates a particular stimulus condition with an appropriate response (e.g., if X-ray contains Feature A, Feature F, and Feature S, then consider Diagnosis Y). Conversion affords an individual the capability to directly apply procedures without having to actively process declarative knowledge regarding step-by-step information about how the task is executed. Transition between declarative and procedural knowledge is referred to as the knowledge compilation phase and is akin to Fitts' intermediate or associative phase.

According to Anderson, attention demands are reduced when domain specific knowledge is compiled into a set of *if-then-statements*, which is referred to as proceduralization. Moreover, composition can also occur, whereby productions occurring in sequence and sharing the same overall goal are collapsed into a single production. A benefit to reducing the number of production rules required to perform a single task is that overall task goals may be achieved in fewer discrete steps. If each processing step is associated with a unit of time, composition allows the individual to save processing time and ultimately leads to greater efficiency in performance. Since fewer steps are required for task execution, it is also postulated

that there is an associated load reduction in working memory since it does not have to be updated as often during the performance of a task.

After declarative knowledge has been compiled into a production system, 'tuning' of the procedure takes place. Improvement occurs as a result of refining the procedure through three processes: generalization, discrimination, and strengthening. Generalization refers to broadening the range of procedure applicability; discrimination denotes the narrowing of rules to fit only appropriate situations; while strengthening implies the weakening of poor rules and the strengthening of better ones (Proctor & Dutta, 1995), all of which enables the individual to execute productions in a fast and reliable manner. As learning progresses from the application of explicit knowledge to implicit knowledge, the contents of working memory are dramatically reduced so that it contains only initial condition and final products of performance. The production rules no longer resemble the original declarative knowledge. Moreover, when individuals are asked to verbally describe their performance strategy they are often unable to do so. This occurs because skilled performers no longer use working memory to describe how a task is executed. Instead, individuals must reconstruct what must have taken place during performance. Once again, according to this perspective, processing at later stages of learning does not imply processing without attention; rather, processing involves a different way of attending relative to early stages of acquisition.

Is Bypassing Attention a Good Thing?

Automatic processing has always been viewed as a highly desirable characteristic and is a general aim of motor learning - an idea that has become heavily entrenched in traditional theories of skill acquisition. However, discussion pertaining to the costs of automatic processing has been largely ignored within the literature. For example, Schmidt (1987) has stated that research has focused "too heavily on the benefits received from automatic processing in skilled performance without considering sufficiently their costs" (p. 100). Moreover, some theorists have challenged whether true automaticity (as defined by capacity-free processing)

should even be a desirable state of behaviour. This latter idea is briefly discussed with respect to error detection and correction capabilities and deliberate practice.

Error Detection and Correction

According to the original definitions proposed by Schneider and Shiffrin (1977; Shiffrin & Schneider, 1977), controlled processing is: under intentional control, limited by the availability of processing resources, effortful, and flexible in response to changes in the environment. In contrast, automatic processing was defined as unintentional behaviour, which does not use any processing resources, and is effortless. Importantly, their original theory posits that once an automatic process is initiated, all processing runs to completion in lieu of subject intervention. This makes control, modification, and/or suppression of the current action extremely difficult, if not impossible. From this perspective, 'less control' is equated with the execution of involuntary responses that occur outside of awareness. However, this conceptualization poses a problem for the observation that skilled performers appear to possess greater control and awareness of well-developed movement skills (Ivry, 1996). One such example is the capability to detect and correct movement errors during the execution of a task.

According to closed-loop theories of movement control, an individual compares his or her current output to an internalised standard of correctness during the execution of a movement. It is further hypothesized that any difference between the output and input is then fed to the executive level of processing, which acts to reduce the discrepancy to zero. As such, discrepancies must be brought into conscious awareness by way of system monitoring if an action is to be altered during performance. In accordance with Schneider and Shiffrin's (1977; Shiffrin & Schneider, 1977) conceptualization, skilled individuals should exhibit a diminished capability to detect errors when compared to novice (or less skilled) performers. Such a prediction, however, is contrary to a number of skill acquisition theories (e.g., Fitts & Posner, 1967). Empirically, Schmidt and White (1972) have provided evidence suggesting that error detection capabilities are enhanced as a function of practice. Using a ballistic timing task, Schmidt and White (1972) asked participants

to verbally estimate their movement time immediately following the performance of the movement task. The difference between the participant's evaluation of movement time (subjective error) and actual movement time (objective error) was calculated, and within subject correlations were computed. Findings revealed that as practice progressed, there was an increasing correspondence between the two error scores suggesting that error detection capabilities were enhanced as a function of practice. Recently, Bredin and Bouffard (2000) and Bredin, Hodges, Sturrock, Franks, and Chua (2000) have demonstrated similar findings by examining the error detection and estimation capabilities of skilled and novice performers following the execution of complex motor tasks (i.e., the full golf swing and the golf chip, respectively). Although these studies did not use an on-line error detection task, this evidence still suggests that characteristics exhibited by skilled performance (e.g., the capability to detect error) may only manifest as a result of an increased capability for controlled processing, not its elimination. Other empirical evidence demonstrates that skilled typists are able to inhibit high speed typing within one or two keystrokes of detecting an error (Rabbitt, 1978) or upon the occurrence of an overt signal to stop (Logan, 1982). As such, it appears that skilled typists exhibit very close control over his/her typing by monitoring each individual keystroke. Therefore, controlled processing (via attention) is an essential component for on-line detection and correction of error. At higher levels of skill acquisition, controlled processing is not eliminated, but appears to become highly specialized (Ivry, 1996).

Automatic Processing Arrests Development of Skilled Performance

Recently, Ericsson (2003) has argued that automatic processing actually arrests the development of skilled performance. When acquiring a task such as skiing or tennis, individuals attempt to gain an acceptable level of mastery as quickly as possible. Ericsson suggests that for most recreational levels, individuals take approximately 50 hours to progress from the cognitive phase of learning through to the autonomous stage, whereby the individual has reached a fairly stable level of performance that does not demand high levels of attention. In contrast to Fitts and Posner's three-stage conceptualization (1967), Ericsson asserts that improvements

will not emerge with further experience on the task. Experts, in contrast, resist performing in an automatic mode by remaining in the cognitive/associative stages. It is only when the performer deliberately attends to the continual refinement of the mental representations associated with task performance that further improvement occurs. When the individual stops engaging in deliberate practice performance will subsequently fall into automated modes of control, arresting further development of the skill. In essence, deliberate practise prevents an individual from 'premature automation' (p. 65), which prevents the learner from achieving higher levels of performance. Although attractive, this theory is not without its problems (also see Abernethy, Farrow, & Berry, 2003). For example, the tenets of this theory would predict that the expert should experience greater dual-task interference in comparison to the non-expert. Instead, empirical research, including the results of the present investigations (Experiments 1-3, & 5), demonstrate that dual-task interference decreases as a function of practice. Nevertheless, this conceptualization warrants further investigation for a better understanding of attention demands and skilled motor performance.

Attention Demands, Augmented Feedback and Bimanual Coordination

One important issue for the acquisition of bimanual coordination tasks has been the finding that pre-existing coordination tendencies appear to disrupt the learning process. Therefore, a major difficulty of learning is breaking away from pre-practice behaviours, as well as resisting the influence of intrinsic patterns when task conditions change. To break away from pre-existing coordination biases, individuals may use a number of information sources. Therefore, a secondary purpose of this thesis was to examine the effects of two such sources for the acquisition of a new bimanual coordination pattern. Specifically, we examined the role of continuous on-line visual feedback and manual guidance. Visual feedback was provided by plotting relative motion displacement plots in real-time, while manual guidance was provided via a set of servo torque motors, which moved the participants' limbs in the required phase relation, as well as in a summary playback of their own performance. In all of our experiments, availability of concurrent visual feedback was manipulated so that

visual feedback was either removed from the perceptual display (while performing the 90° task) or became available during a trial to guide execution of the movement. By manipulating availability of real-time relative motion feedback we were able to assess changes in attention demands while performing the goal coordination task.

Across experiments, findings revealed that the 90° pattern was more accurate in the presence of visual feedback regardless of whether vision was presented in the first segment or the second segment of the trial. Importantly, when visual feedback was removed from the perceptual display during a trial, a relatively permanent phase drift occurred towards the more preferred coordination tendency of anti-phase (Experiment 1). This observed phase drift was considered relatively permanent because performance did not return to the same levels of accuracy and stability exhibited prior to removal of the feedback, even when time was provided to recover from the environmental disruption (Experiment 5). When visual feedback was unavailable to guide on-going movement in segment 1, participants were generally unable to inhibit the influence of pre-existing tendencies until much later in learning, or in some cases, not at all (Experiment 2). However, our findings showed that using servo torque motors to physically guide the learner's limbs provided some learning benefits when visual feedback was limited and individuals were left to their own devices to learn how to produce the task (Experiment 3).

With respect to attention demands, the present series of investigations demonstrated that attention demands increase whenever information feedback sources are switched. Increases in attention demands may be temporary, or more permanent depending on the nature of the switch. Providing visual feedback in the middle of the trial (after performing in its absence), only temporarily increases attentional load, while switching from visual to proprioceptive sources produces a more permanent effect. This latter finding can be explained by the fact that performance of the 90° pattern was shown to be less attention demanding in the presence of real-time relative motion feedback than when performing in its absence. A possible explanation provided for the latter observation was the use of relative motion displacement plots. It was postulated that presenting spatiotemporal information in the form of a Lissajous figure may decrease attention demands and

facilitate learning of the new pattern because the trace clearly specifies the task goal, and provides performers with crucial features of the movement. This alerts the individual to the properties and relationships inherent within the task in lieu of specific task instructions. This finding may be particularly important when discussing instructional aids for older adults experiencing decreased learning as a result of normal aging. For example, Wishart, Lee, Cunningham, and Murdoch (2002) have shown that elderly individuals experience large benefits from the provision of concurrent visual feedback when learning a 90° out-of-phase task. One reason for this benefit may be that attention demands of the task are reduced when visual feedback is provided. The relative motion displacement plots presents the individual with information that they do not necessarily have to find on their own, thereby reducing cognitive load and facilitating acquisition of the required pattern. Clearly, further work is warranted for understanding the relationship between attention demands and the use of different feedback sources for the acquisition of a new bimanual coordination pattern in a wide variety of populations (e.g., children, the elderly, motor disordered patients). Moreover, the findings of the present series of investigations provide support for utilizing experimental designs that observe learning across extended periods of practice, in comparison to the number of practice trials typically employed in motor learning experiments. Such experimental designs provide new insights into the acquisition of bimanual coordination patterns and how attention demands evolve across the time course of learning.

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APPENDIX A REVIEW OF LITERATURE

UNDERSTANDING LEARNING PHENOMENA: A FOUNDATION

The literature presented and discussed within the main body of this thesis has been constrained to content directly related to the empirical investigations contained within. As such, the purpose of the following appendix chapter is to provide a more detailed description of central concepts not permitted within the selected format, as well as present concepts that are closely linked and lay the foundation (or rationale) for the preceding line of empirical investigations. The intent here is to provide the reader with an enhanced description of concepts relating to skill acquisition from two distinct theoretical approaches to motor learning. Specifically, the learning process will be discussed from both an information-processing framework, as well as from a dynamical systems view of motor learning and control. Rationale will also be provided in support of an integrative experimental approach whereby qualities of both perspectives are combined to examine the learning of complex, coordination patterns.

The content of this chapter is presented in four sections. First, discussion will focus on understanding the complex nature of skilled behaviour. The second section will then examine skill acquisition from a human information processing perspective. Emphasis will be given to discussion on representational-based accounts of skill acquisition, the role of attention within these frameworks, as well as the relationship between attention and automatic processing for human motor performance. The third section will shift theoretical approaches to discuss motor learning from a dynamical systems perspective. Emphasis here will be on understanding the basic tenets and concepts of dynamic pattern theory and how the tools afforded by nonlinear dynamics can explain the acquisition of complex coordination patterns. In the fourth, and final section of this review, both theoretical positions will be brought together, and discussion will focus on the potential role of each framework for future exploration of motor learning phenomena. Specifically, an integrative approach for empirical investigation will be advocated with a particular emphasis on experimental designs that incorporate features central to both of these theoretical positions.

SECTION ONE

The Nature of Skilled Behaviour: An Introduction

"Skill consists in the ability to bring about some end result with maximum certainty and minimum outlay of energy, or of time and energy" (Guthrie, 1952).

The term 'skill' is used to communicate a quality of performance or degree of proficiency, which is often subjectively established by characteristics of performance (e.g., consistency) or how well the goal of the task was accomplished (e.g., outcome, degree of productivity) (Magill, 1993)¹. As this operational definition suggests, skill cannot be directly observed, rather it is inferred through performance. Furthermore, skilled action does not manifest as an absolute, all-or-none phenomenon. Instead, skill is a relative term whereby individuals vary in their degree of proficiency (Patrick, 1992) and the line between what does or does not constitute skilled performance is tenuous at best (Logan, 1985). This latter statement is particularly accurate when trying to determine what constitutes motor expertise. For example, the normal individual achieves a high degree of competence and proficiency in many everyday tasks. From most perspectives, however, the cultural label of 'motor expert' is bestowed only upon those individuals who achieve excellence on tasks that are not part of the movement repertoire of the normal population (Starkes, 1993). Stated differently, "who we class as an expert depends on the relative exclusivity of the skill" (Starkes, 1993, p. 3). Moreover, this problem is further complicated in that skilled performance is considered open-ended because humans continually surpass current standards of motor performance to achieve new heights. In figure skating, for example, the inclusion of one or two triple jumps was once considered a highly competitive and demanding program at the international level. Today, a male skater does not perform a jump smaller than a triple and within his repertoire must possess 'quad' jumps if he is to challenge on the world stage.

¹ In general, the word 'skill' may take on different meaning depending on the context of its usage. For example, in one context, one might say, "that individual is a highly skilled driver". However, in a different context, the sentence, "tracking is an essential skill for driving a car", may be the appropriate word connotation (Magill, 1993). To eliminate any misunderstanding in this thesis, the term 'skill' is used to indicate one's quality of performance; whereas, the term 'action' or 'task' will generally be used to refer to a motor skill, which is defined as voluntary physical goal-directed movement of the body and/or limb in a highly specific response sequence (Magill, 1993).

This implies that performances garnered by today's expert level sport performers may eventually be surpassed by the endeavors of future performers.

Vast strides in sport performance are usually attributed to a range of factors. Some of which relate to the human element (e.g., improved levels of fitness, knowledge, and prerequisite techniques), while others are associated with advances in material technology (e.g., improvements in sports equipment design and the materials used in its construction). Consequently, high performance standards have led to an increased trend towards specialization (Ericsson, 1996). Moreover, the capabilities rendered by the learning process are specific to the task practiced (Keele & Hawkins, 1982), whereby transfer across elite domains in which the performer has no experience is limited. Only in rare instances are sport performers able to obtain an international level of performance in another field - occurring only when the activities are highly related and consistent with the individual's current and past training (Ericsson, 2003). Given these types of problems, a universal definition of what constitutes expert performance is unavailable (Salthouse, 1991). However, it is generally accepted that expert performance refers to consistently superior performance on a specified set of representative tasks for a particular domain (Ericsson & Lehmann, 1996).

Perspectives of Expert Performance: Innate Talent or Practice?

Outstanding performance has been a popular topic of discussion within the literature, and has been debated from two perspectives. The first view suggests that individual differences reflect innate capacities or attributes, also referred to as 'talents' or 'gifts', which cannot be modified by practice. Although instruction and practice are necessary to reach expert levels of performance, a talent-based approach postulates that these factors are not the primary antecedents for attaining outstanding performance. Instead, stable, genetically determined factors limit the level of performance achieved by the individual. A central tenet of this perspective is also the notion that innate talent in a particular domain can be detected at an early stage, which provides a basis for predicting future success. As a result, proponents of this perspective have traditionally focused empirical research on the early

identification of talent in various types of activities (see Howe, Davidson, & Sloboda, 1998, for a review).

Although the talent account of expert performance has been at the centre of much discussion, little empirical evidence has surfaced to support the 'nature' argument. In contrast, a second, more contemporary perspective has emerged at the opposite end of the continuum, which suggests that skilled performance is primarily mediated by the accumulated duration of systematic training, and arises irrespective of genetic factors or hereditary predispositions (Janelle & Hillman, 2003). According to Ericsson and colleagues (see 1993, 1996, 2003, for examples of perspective), empirical evidence clearly demonstrates that a wide range of human characteristics, including both anatomical and physiological constraints, as well as cognitive and perceptual-motor skills, are modifiable as a result of extended and appropriately designed practice. It is well documented, for example, that heart size, number of blood-supplying capillaries, and metabolic properties of critical muscles change because of long-term, highly intense practice. Findings also reveal that anatomical and physiological adaptations are especially dramatic at young ages when the body is still at the early stages of its development. Intense training leads to specific stimulation of the body far beyond the normal range encountered in everyday living. For example, exposure to early and appropriate training increases the turnout of young classical ballet students (Ericsson & Lehmann, 1996). In fact, the only genetic exception to the 'nurture argument' has been height and body size, which appears to constrain an individual from reaching high levels of performance in such activities as basketball and gymnastics.

According to a strict practice approach, individuals do not require innate talent to achieve expert levels of performance. Rather, differences in early experiences, preferences, opportunities, habits, training and practice are the real determinants of excellence (Howe et al., 1998). Given these factors, a central tenet to this perspective is the idea that everyone has the potential to achieve expertise. Evidence that provides support for the causal role of practice in attaining expert performance shows that individuals cannot attain exceptional performance on a task without extended appropriate practice. Furthermore, when randomly selected

individuals engage in training, improvements in performance are a direct result of the experimental protocol (Ericsson, 2003).

In response to the emergence of an extreme 'nurturist' perspective, some researchers advocate a more 'interactionist' approach to expert performance. From this perspective, it is postulated that expert performance is mediated by a combination of both genetic and environmental factors. Although practice plays a critical role in the development of expertise, they do not deny the influence of innate hereditary factors on level of acquirable expertise (Janelle & Hillman, 2003).

The preceding line of investigations sought to explore changes in attention demands as a function of extended practice. Therefore, the rest of this review of literature will focus on the role of practice in skill acquisition; rather than on innate talents of a performer.

Acquiring Task Proficiency

To achieve excellence, individuals must expend considerable time and effort in an attempt to develop an action behaviour that is proficient, effective, and remarkably consistent in nature (Schneider, 1985). For example, Anderson (1982) asserts that the significant acquisition of cognitive skill requires at least 100 hours of training if an individual is to perform with a reasonable degree of proficiency. Moreover, many complex skills require years of intense practice before a high level of proficiency is ever attained. Using chess play as one such example, Simon and Chase (1973) have reported that achieving the highest level or rating of skill (i.e., Grandmaster) requires no fewer than nine or ten years of intense and extensive preparation. Work by Bloom (1985) and Ericsson, Krampe, and Tech-Römer (1993) have provided support for the generalizability of this '10-year rule', which appears to hold for a wide variety of other skills in both the cognitive (e.g. mathematics) and motor domains (e.g. swimming). It should be noted, however, that many individuals spend considerably longer than 10 years in attaining international levels of performance.

In addition to length of time, a critical factor in achieving a level of expertise is the type of practice an individual engages in. To achieve superior levels of

performance, Ericsson and colleagues maintain that the learner must undertake a form of practice called deliberate practice (see Ericsson, Krampe, & Tech-Römer, 1993 for original discussion). In contrast to play, deliberate practice is a highly structured activity, requiring a large commitment of time and energy, as well as other resources (e.g., access to instructors, materials, or training facilities). Strictly motivated by its instrumental value for improving performance (rather than immediate extrinsic reward or financial gain), deliberate practice is not viewed as an inherently enjoyable activity in general. Interestingly, research in the sport domain has shown evidence suggesting that athletes tend to deem a variety of practice activities as enjoyable (e.g., mat work in wrestling, on-ice training in skating) (see Helsen, Starkes, & Hodges, 1998; Hodge & Deakin, 1998; Starkes et al., 1996). However, sport performers will still classify practice activities as less enjoyable when comparing them with such everyday activities as sleep and leisure (Starkes, 2000). According to Ericsson (1996), athletes who express a positive assessment of enjoyment, are usually referring to the social nature of sport, and not necessarily responding to the structured elements of the practice environment.

Another characteristic of deliberate practice is that large amounts of concentration and effort are required on the part of the individual to maximize improvement gains. Therefore, an effective level of daily practice is only sustainable if the individual is limited to a time-frame that allows the performer to adequately recover between sessions. As such, reaching expert levels of performance is not entirely dependent on the number of practice hours. Instead, it is the structure and content of the practice sessions that is of paramount importance. Moreover, Ericsson et al. (1993) propose a monotonic relationship between expert performance and deliberate practice, whereby increases in hours of deliberate practice directly translates into associated levels of improvement in performance. Therefore, cumulative hours of deliberate practice should be a good predictor of the level of performance attained by the individual.

Investigating Practice

In essence, transition from inexperienced to skilled states of behaviour largely manifests as a function of practice or experience. By way of practice, individuals acquire a set of processes that leads to a persistent or permanent change in their capability for performance. Known as the field of motor learning, researchers interested in examining the learning process, are concerned with understanding the nature of this change. Therefore, the questions that give rise to empirical investigation typically ask: what has the performer learned; what types of practice enable and facilitate the acquisition process; and what are the time-periods over which change occurs (Hodges, 2001)? Interestingly, these questions are common to two different theoretical perspectives. The first discusses motor behaviour from an information-processing framework of human performance, while the second is known as the dynamical systems approach. A principal feature of theories derived from an information-processing premise (e.g., feedback-based learning theories and motor programming theories) is the existence of centrally stored internal representations, acquired as a function of practice, which are used as a basis for regulating and controlling desired actions of the performer. From this perspective, traditional research paradigms from cognitive psychology are applied to the motor domain in an effort to understand the acquisition of skilled behaviour. In contrast, theories based on the more radical dynamical systems approach, reject the assumption of central representations. Dynamical systems theorists argue that behaviour results from the interaction of multiple system components (e.g., the interaction between body parts, and between body parts and the environment) whereby no one system component prescribes the action of the performer. Because of this interplay of forces and mutual influence between system components, the motor system spontaneously self-organizes towards preferred states or patterns of behaviour that arise under certain conditions. Using mathematical tools from nonlinear dynamics, this approach to motor learning seeks to understand how both coordination and control of the body are achieved in providing solutions to a new movement problem (Vereijken, 1991).

SECTION TWO

Skill Acquisition from an Information-processing Perspective

Prior to the 1950's, the prevailing paradigm that guided scientific research in psychology was the behaviourist perspective, whereby scientists directed their line of inquiry to investigations pertaining to the relation between environmental information (the stimuli) and resultant action (the response). With the emergence of cognitive psychology in the 1950's, a shift in research focus towards an information-processing framework occurred, where scientists now concerned themselves with processing events that occurred in the "black box" of the mind. That is, the processing events that occur *between* the presentation of a stimuli and the execution of an individual's motor response.

According to proponents of the information-processing model of human behaviour, mental functioning is considered analogous to the operations of a computer. Individuals take in information from the environment, this information is stored in various memory systems to be processed, and finally, after a complex chain of processing activities, a response or output is made. Such an approach suggests that a performer's behaviour is mediated by transactions of information between the individual and the environment (Whiting, 1978). Therefore, humans are not only independent of their environment, but act as *active* processors of information (Slife & Williams, 1995). Emphasizing "mental operations that precede a motor act, rather than the act itself" (Goodman, 1985, p. 319), theoretical consideration is directed toward the cognitive activities that underlie motor behaviour.

Inherent within the information-processing framework are several key assumptions. First, it is assumed that a number of processing stages exist between the presentation of a stimulus and the production of a response, and each stage can be identified. Second, each stage represents an operation, and therefore, requires time for execution. Third, operation at each stage can only be conducted on information that has been made available for processing. Finally, information is transformed at each stage and is then passed on to the next processing stage (Goodman, 1985). Based on these assumptions, it is suggested that cognitive

processes sub-serve action by modifying and selecting the information that gets into the system, as well as the information that passes through each processing stage. As such, this approach assumes a top-down 'executive level' of functioning, whereby control of movement is carried out by what has traditionally been referred to as a 'homunculus' or "little man inside the head" (Turvey, Fitch, & Tuller, 1982, p. 239). Such a perspective gives rise to models of movement that are both prescriptive and hierarchical in nature.

A typical information-processing model of human performance (presented in Figure A1) postulates that there are at least three intervening stages mediating information, which are based upon perceptual, cognitive, and motor processes, respectively. The perceptual mechanism is responsible for identifying and classifying incoming information from the environment, as well as transmitting a description of the environment to the decision mechanism. The function of the decision mechanism is to then formulate a course of action based upon the description of the environment, the individual's past experiences, as well as his or her current objectives. Once a course of action has been chosen, the effector mechanism receives a sequence of commands. A suitable muscle response is then organised and muscle commands are transmitted to the musculature for execution of the response. Both intrinsic and extrinsic forms of feedback play important roles within the information-processing model in that it allows for the detection and correction of movement error since feedback information may be fed back into the system by way of the effector and perceptual mechanisms (Marteniuk, 1976).

Any model that seeks to describe human information processing must take into consideration the mediating influences of attention and memory in cognitive processing. For example, there is a tendency to view attention as the executive mechanism or "unitary source of control" (Stelmach & Hughes, 1983, p. 80) modifying and selecting what information gets into the system, as well as what passes through each processing stage for the accomplishment of perceptual, cognitive, and motor aspects of the task (Klein, 1978). As a consequence of selective stage processing, individuals often respond to the presentation of identical stimuli in a rather diverse manner. The performer not only has to consider the

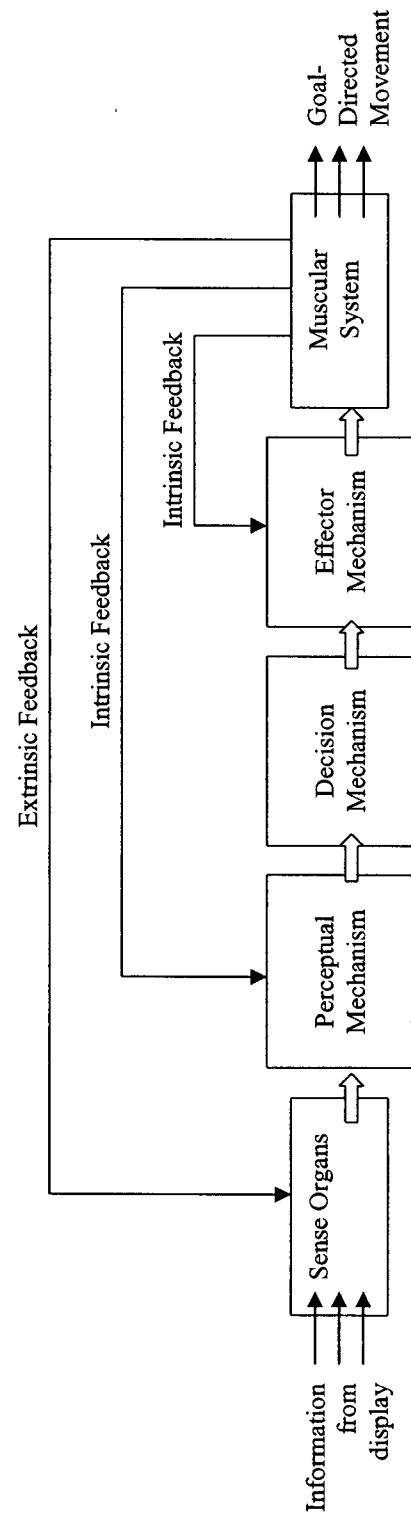


Figure A1. Whiting's (1975) human performance model as depicted in Marteniuk (1976).

current circumstances for the proficient execution of a movement, but he or she must also retrieve information from long-term memory to plan and execute the movement. Control of motor performance is achieved by accessing an existing motor plan (or program) from memory, or by synthesizing a new plan from various subroutines in memory (Goodman, 1985). As such, cognitive theory for human performance mandates that (a) "some kind of symbolic *representation* of the intended movement is necessary to allow the mind, body, and environment to interact", and (b) "the body is essentially subservient to the mind" (Abernethy, Burgess-Limerick, & Parks, 1994, p. 188).

Representational-Based Accounts of Skill Acquisition

The term 'representation' (see italics at the end of the preceding section) refers to the psychological structures and processes that allow an individual to utilize past experience for the improvement of motor behaviour (Ivry, 1996). Therefore, the information processing perspective posits that motor learning results from comparisons between an individual's memory representation of the movement and the actual result produced by the performer's action. Such comparisons serve to develop, refine, and strengthen a representation, which ultimately leads to a persistent or permanent change in resultant behaviour over time.

Classic Theories of Skill Acquisition

A number of representational-based accounts of skill acquisition have appeared within the motor control and learning literature (e.g., Gentile, 1972, 1998; Whiting & den Brinker, 1982). The most commonly cited framework is Schmidt's (1975, 1980) schema theory. Specifically, the term schema refers to an abstract memory representation of an event or action, which can also be thought of as a rule, concept, or generalization. Using the basic idea of the schema, Schmidt proposed a theory of skill acquisition, which has played a central role in theoretical development of the field (Schmidt & Lee, 1999).

Schmidt's (1975, 1980) Schema Theory. Upon the execution of a movement, Schmidt (1975, 1980) posits an individual can store four types of information: 1) the initial conditions of the movement; 2) the specifications or parameters of the response; 3) the outcome of the response; and 4) the sensory consequences of the action. From this information, two movement representations, or abstractions, develop in memory. Referred to as schemata, these abstractions are responsible for initiating the movement, as well as evaluating its success during and/or after its completion. The first schema, identified as the recall schema, enables the performer to select and initiate the required parameters of the movement (i.e., the motor program). Motor programs (acquired by learning) control movement execution, much like software programs in computers. The second relationship, the recognition schema, is responsible for evaluating response-produced feedback and informing the performer about the direction and amount of response error. Using the information stored in memory, the performer estimates and compares expected sensory consequences of an action to actual response-feedback. Any discrepancy between the expected and actual sensory consequence produces an error in movement response giving rise to a sensory signal that is fed back to the schema so that adjustments can be made by the performer to reduce the error to zero. As such, the recognition schema acts as a reference mechanism, enabling on-line and off-line error detection and correction, which is largely determined by movement duration.

To account for rapid ballistic movements, schema theory suggests that a movement can be executed without the use of feedback control processes. In this manner, it is postulated that the performer executes the task using open-loop processes or motor-program control, whereby movements are programmed in advance since there is not enough time to modify the movement on-line. In tasks of ample duration, processes operating in a closed-loop fashion may control movements. Closed-loop control allows the individual to use sensory feedback to modify the movement during its execution. However, it is also postulated that movements very long in duration can also be controlled by open-loop control after an extended period of practice. At early stages of learning, the individual lacks an adequate motor program for carrying out the action. With practice, the individual is

able to establish an abstract representation of the action using feedback-based control processes. Eventually, the system acquires a motor program capable of running off long sequences of action with little cognitive effort (Schmidt, 1987). In essence, a highly skilled performer, equipped with a strong motor program, gains the capability to shift from a feedback-based mode of control to a programmed mode, whereby movement is produced without regard to sensory information when activated (Schmidt & Lee, 1999). According to Schmidt, control flexibility is advantageous in that the performer can direct needed attention towards higher-order aspects of the movement since the action itself can be performed without interfering with other cognitive information-processing tasks (Schmidt, 1980, 1987). In addition, the individual can save effort when accuracy requirements of a task are not critical, or the costs of committing an error are minimal. This statement is based on the assumption that feedback-based modes of control require attention, and attention facilitates accuracy on a task. Therefore, due to an inherent trade-off between accuracy and attentional costs, it is postulated that skilled performers can shift from one mode of control to the other depending on the accuracy demands of the task (Schmidt, 1980).

Phases of Skill Acquisition

Inherent to many representational-based accounts of learning is the notion that skill acquisition proceeds in phases, whereby performance characteristics of the individual are observed to change in a qualitative way. Acceptance of a 'phase approach' to skill acquisition has laid the foundation for much of the empirical work and theoretical development that has occurred within a variety of domains (e.g., instructional pedagogy). Generally, theoretical discussion has focused on two (e.g., Adams, 1971; Gentile, 1972) or three (e.g., Anderson, 1982; Fitts & Posner, 1967) distinct stages of acquisition, although empirical investigation typically focuses on the early, initial acquisition stages when a learning paradigm is employed (Adams, 1987).

Common to each of these perspectives, is the idea that during the initial phase of acquisition, learners are first preoccupied with getting the idea of the

movement. After realizing the general requirements of the task, practice then advances to where the individual is concerned with skill refinement. Finally, a few individuals will advance to an even higher level of practice, characterized by performance that appears to be executed with little or no effort on the part of the performer (Wrisberg, 1993). Embedded within these frameworks is the assumption that one mode of processing dominates early phases of learning and another mode of processing governs movement behaviour late in skill development.

To demonstrate this latter notion, both a two- and three-phase framework of skill acquisition will now be presented. These include Adams (1971) closed-loop theory of motor control and Fitts' (1962, 1964; Fitts & Posner, 1967) three-phase theory of acquisition, respectively. Adams' (1971) closed-loop theory of motor control is a framework derived from the influences of cybernetics and servo-control mechanisms. Although its primary emphasis is on the role of feedback in skill acquisition and the development of error detection capabilities, it is also a theory of verbal-motor learning. Central to this perspective is the idea that humans regulate their movement at initial stages of learning through the covert use of verbal responses. This theory of motor control and learning was formulated in criticism of Thorndike's (1914) Law of Effect², a major influence of the time in psychology, which implied "an automatic, non-cognitive nature of learning" (Adams, 1971, p. 115). In contrast to Adams, Fitts (1962, 1964; Fitts & Posner, 1967) adopted a three-phase theory of skill acquisition. Proposed over thirty years ago, this theory has played a highly influential role within the motor learning literature. Although this framework was strictly based on observations and interviews with instructors from a wide variety of motor domains, it has a common sense appeal, which has led to its ubiquitous use.

² Thorndike's (1914) Law of Effect, often restated as the principle of reinforcement, is an empirical statement, which claims that learning is related to the presence of rewards or punishments following a response. If a response is closely followed by a rewarding event, the response will be repeated. If a response is closely followed by a punishing event, elimination of that response will follow. Although Thorndike began his work with animals, he went on to extend the use of the Law of Effect to human learning in the classroom and laboratory setting. However, extending the Law of Effect in this manner assumes that laws governing animals also govern learning in humans (see Adams, 1971 for arguments in criticism of this assumption).

Adams' (1971) Verbal-Motor and Motor phases of Learning. According to Adams (1971), movements are made by comparing ongoing feedback from the limbs during the execution of a movement to an internal representation (or reference of correctness) that is developed as a result of practice. The formulation of the internal reference of correctness is based on the notion that sensory information available during the execution of a movement leaves a trace or "image" in the central nervous system (CNS) that is stored by the learner from each movement response. As a learner becomes more proficient at a skill, discrepancies between the 'perceptual trace' and criterion will decrease and the distribution of accumulated traces will gradually represent the feedback qualities of the criterion response. Movement is subsequently guided or directed by making comparisons between the sensory information arising from the movement response (i.e., response-produced feedback) and the perceptual trace of the desired outcome. If current response-produced feedback does not match the perceptual trace, a discrepancy or error is detected, and a discrete correction is executed on the part of the performer. This error analysis continues until no discrepancies are detected between the response-produced feedback and the perceptual trace. In this manner, movement is regulated by an error nulling process, and successful performance centers on the quality of the perceptual trace.

Adams suggests that knowledge of results (KR) plays a fundamental role in the development of the perceptual trace. Information about the outcome of each trial strengthens the trace because it is used to drive the movement closer to the criterion. That is, the distribution of traces laid out early in learning if KR is provided should represent a closer approximation of the correction response than if KR was not present. Using KR implies that the learner is an active participant in the learning process, whereby the information content of the KR (and verbal transforms of it) is covertly used to regulate movement at initial stages of acquisition. Wanting to emphasize the cognitive nature of learning, Adams labelled this developmental phase as the 'verbal-motor stage' of skill acquisition.

When the perceptual trace is adequately developed (i.e., the error reported in KR is minimal over a long period of time), Adams suggests that learners possess the capability for recognizing their own performance errors without a reliance on external sources of information. In fact, at this phase of acquisition, it is postulated that performers can ignore KR and learning can continue to occur even in its absence. As Adams has stated, "the specifications for the correct response are within him [the performer] in the form of a strong perceptual trace and, in relying on it for movement, he can make the correct response over and over and strengthen the perceptual trace even more" (p. 125). This form of learning has been referred to as subjective reinforcement and is illustrative of Adams final 'motor stage' of learning.

Most simply, the learner passes from a 'verbal-motor' stage of movement production to a purely 'motor' stage when the learner no longer relies on mediation by thought or augmented feedback. Knowledge of results can be withdrawn from use since the capability to detect and correct errors is based on an internalized reference of correctness. Moreover, Adams supports the idea that passage from the verbal-motor phase to motor phase of learning implies that conscious behaviour has become automatic. At initial phases of learning, movement is regulated by the covert use of verbal responses (or cognitive activity), while late phases of skill acquisition are characterized by an increased adeptness in *serial* regulation of movement (Lee & Swinnen, 1993).

Fitts' Three-Phase Theory of Skill Acquisition. Fitts and colleague (1962, 1964; Fitts & Posner, 1967) proposed that the process of acquiring skill involves a progression through three phases: the cognitive phase, the intermediate or associative phase, and the autonomous phase. These phases overlap and the transition from one to the other is continuous, marked by gradual, rather than abrupt, transitional shifts. In fact, any distinctions made between these phases are made somewhat arbitrarily and merely represent different aspects along the learning continuum.

In the initial phase of acquisition, the learner is presented with a to-be learned task. According to Fitts, the learner's primary focus of attention is directed towards

understanding the nature or expectations of the task, identifying how the task should be performed, as well as involved in the formulation of performance strategies based on strategies developed from previously learned tasks. As the learner determines how best to attempt the first few preliminary trials, it is necessary for the individual to attend to cues, events, and responses that go unnoticed in later stages of learning. It is also at this phase that the learner becomes familiar with the formal procedures (e.g., rules) governing the task. As such, a considerable amount of cognitive activity (or effort) is required on the part of the learner, hence the designation 'cognitive phase' of learning. Inconsistency and gross errors in performance are evident within this acquisition phase as the learner attempts to generate responses that crudely approximate the desired form of the behaviour by trying a variety of ways to solve the movement problem. At this point, Fitts and Posner (1967) state that, "behaviour is truly a patchwork of old habits ready to be put together into new patterns and supplemented by a few new habits" (p. 12). Performance gains are very dramatic, and are generally larger than the performance gain(s) at any other single period of time within the acquisition process.

Once the learner is able to identify the perceptual and response components of a task, the learner begins to link common sets of stimuli to common sets of responses in a probabilistic manner. This behaviour marks a transition to the intermediate or associative phase, which is characterized by the learning of cognitive "sets". According to Fitts, a cognitive set signifies advanced preparation on the part of the learner for the contingencies, which distinguish a particular situation. Procedures learned in the early stage of acquisition have been attempted, and movement patterns begin to emerge as individual components of the skill become pieced together. The learner's focus becomes directed towards 'smoothing out the skill' by making adjustments to the pattern. These small changes result in a more effective movement pattern evidenced by fewer errors and increased consistency in performance. Errors that do occur manifest as a result of grossly inappropriate subroutines, wrong sequences of acts, or as responses to incorrect cues. Duration of this stage is dependent on the complexity of the skill and the extent to which it requires integration and the formulation of new subroutines. For highly complex

skills, the learner is usually engaged in this phase for a longer period of time when compared to the overall time duration of the cognitive phase. An example of the time frame that Fitts (1962) suggested for this phase of learning is demonstrated in the following statement:

"In the case of a typist it would extend from the point at which the student has learned the position of the different keys and how the fingers are used in striking them to the point where he/she has perhaps graduated from his/her first typing course and reduced his/her errors to less than 1 per cent and has acquired a fair degree of typing speed" (p. 188).

Passage into the final phase of acquisition, is marked by relatively few errors in performance as well as a high degree of performance consistency. At this stage, large chunks of behaviour have been 'programmed' and appear to be executed without direct monitoring or sensory control. That is, component processes have become increasingly autonomous, hence the label 'autonomous stage', whereby attention requirements are diminished or lessened and the individual executes most of the skill without thinking about it. Due to the lack of conscious awareness, automatized skills are executed without much verbalization; and, in fact, Fitts and Posner (1967) go on to suggest that overt verbalization may actually interfere with the performance of highly developed skills.

Within this framework, the acquisition of automated behaviour is fundamental in that it affords the individual a number of advantages. According to Fitts, automatized skill components require less cognitive processing on the part of the learner. Therefore, the performer can execute the skill while new learning is in progress. This means that the speed and efficiency with which some skills are performed continues to improve even during the final stages of skill acquisition, although improvement occurs at a continually decreasing rate. If performance should level off, Fitts postulates that this may very well be attributed to the effects of physiological aging and/or a result of a loss of motivation rather than a true learning plateau or limit in the individual's capacity for further improvement. Furthermore, automatization reduces the information-processing load of the performer and

permits the individual to focus on other perceptual and cognitive aspects of the task for optimal performance (e.g., the planning of strategy). Therefore, as automaticity is acquired, the learner also appears to gain a capability to concurrently perform the automated task at the same time as other ongoing activities or environmental distractions. For example, while executing a well-practised task such as driving, many individuals attempt to drive, change the radio channel, and talk to a passenger, all at the same time. At initial phases of learning, a considerable amount of cognitive effort is required on the part of the learner. In contrast, late stages of skill acquisition are characterized by an increased adeptness for *parallel* processing (Lee & Swinnen, 1993).

Summary

An information-processing approach for human performance mandates the existence of a memory representation, which allows the mind, body, and environment to interact for the successful execution of a motor task. As a consequence, two- and three-phase representational-based frameworks of skill acquisition have emerged within the literature. These frameworks serve to describe how the memory representation of an event or action is developed, refined, and strengthened over time. Embedded within these models is the assumption that one mode of processing dominates early phases of learning and another mode of processing governs movement behaviour late in skill development. Specifically, these frameworks assume that learning progresses in phases that can be differentiated on the basis of the cognitive activity associated with the production of the response. Early in learning, a considerable amount of cognitive activity is required on the part of the learner, which diminishes as a function of practice. According to this perspective, diminishing demands on attention is advantageous to the performer in that processing load is reduced, thereby permitting the individual to focus on higher-order aspects of performance.

Investigating the Role of Attention in Motor Performance

At high levels of acquisition, motor behaviour is thought to become automatic whereby a shift from the conscious and deliberate allocation of attention to the non-cognitive regulation of an ongoing movement occurs (e.g., Adams, 1971). At the advanced phase, performers also demonstrate a capability to perform two tasks simultaneously without a decrement in performance (e.g., Fitts & Posner, 1967). As such, understanding the role of attention and its regulation is paramount to understanding the nature of human skill and the development of competence and expertise. In fact, most operational definitions make the assumption that attention is a necessary prerequisite for the performance of a voluntary act³ (Stelmach & Larish, 1980).

Present day interest in attention arose during the Second World War as a result of the practical problems of skilled performance and its breakdown under conditions of 'cognitive load'. This interest was largely enabled by a number of coinciding events of the 1950s, which included the development of computers, the concomitant introduction of information transmission theory, and the introduction of experimental methodologies and techniques for analysing directly observable mental processes (Allport, 1980). As a result of these events, cognitive scientists endeavoured to examine the nature of human performance with a direct emphasis on discovering the attentional limitations of the processing system. In general, the study of attention can be broken up into two areas of study. The first area pertains to the study of the mechanisms, which allow an organism to select one object or message over other messages and is referred to as selective attention. The second area of study is concerned with examining the limitations on the amount of information an organism can select for processing at any given period of time (Hirst, 1986). Referred to as divided attention, discussion will be constrained to this area of study due to the nature of this dissertation.

³ The phrase 'voluntary act' is an important criteria in that our discussion is limited to only tasks requiring voluntary physical movement of the body and/or limb in a highly specific response sequence to accomplish the goal of an action or task (Magill, 1993).

The Study of Divided Attention

When observing the passing of everyday life, it becomes apparent that human behaviour is not constrained to the performance of only one task at a time. Rather, individuals often display the capacity to effectively perform two tasks simultaneously. For example, we are able to walk and talk at the same time, as well as listen to music while reading. However, performing two tasks concurrently can also prove difficult and the quality of performance is often less than if each task had been performed solitarily. While we can talk while walking, we cannot talk while reading, nor can we problem solve while listening (example from Hirst, 1986). Often interference between two tasks arises because the tasks are physically incompatible (e.g. typing this page and eating a sandwich with your right hand) or intellectually demanding (e.g., studying for an exam while trying to keep track of the number of votes at tribal council on *Survivor*). Unfortunately, the reason(s) for interference between many other task pairs remains less obvious (Pashler, 1994).

Within the laboratory, investigation of dual-task performance has utilised a wide range of tasks, differing greatly in degree of complexity. For example, task complexity has ranged from examination of simple reaction time (SRT) to real-world activities like dictation (Pashler, 1994). Explanations of dual-task interference have varied, with three of the most influential theoretical approaches from psychology being: bottleneck (or task-switching) models, cross-talk models, and capacity sharing (or resource) models.

Bottleneck models suggest that the human information-processing system is limited in that selection of two independent tasks is impossible when the tasks require the same mechanism for processing. When the system is dedicated to the operations of one task, a bottleneck is produced, and the processing of the other task must be postponed or otherwise impaired. Bottleneck models have been widely investigated in the psychological literature; however, they are not a central theoretical approach to this dissertation. Therefore, further discussion falls beyond the scope of the present review.

Rather than concentrating on the type of operation to be carried out, cross-talk models emphasize degree of similarity between tasks, or the similarity of the

information being processed in each task. In principle, it is postulated that the parallel execution of two tasks comprised of similar content can facilitate dual-task performance if the same mechanism is required for processing. Once one processor is active, it should be more efficient to use the same processor than activating two different processors for concurrent performance. Unfortunately, theorists generally oppose this view; favouring the idea that similarity of content actually intensifies interference between concurrent tasks (Pashler, 1994, 1998).

The third and most widely accepted theoretical explanation of dual-task interference is the one proposed by resource or capacity-sharing models. Since the empirical investigations in this dissertation followed the theoretical tenets of resource theory, an expanded discussion regarding this framework is necessary.

Capacity-sharing (or resource) models. Resource theories assume that people share a limited pool (or pools) of processing capacity (e.g., Kahneman, 1973; Navon & Gopher, 1979; Wickens, 1980, 1984). When two tasks operate in parallel, this limited resource capacity may be partitioned in a flexible and voluntary manner. Efficiency then is dependent on the amount of resources allocated to each task. As the demands of a task increase, fewer resources become available for other tasks. When two concurrent tasks tap into the same resources and/or joint demands exceed the total capacity of available resources, a dual-task decrement incurs in one, or in both of the simultaneously performed tasks – a behavioural outcome referred to as interference. For example, given tasks A and B, interference may be demonstrated by: a) a deterioration in the performance of B, while A remains relatively unaffected; b) a decline in A, while B remains unaffected; c) worsening of performance in both Tasks A and B; or even more drastic, d) complete prevention of B during the execution of A (Schmidt & Lee, 1999). If the performance of one task deteriorates when combined with another task, theory posits that both tasks are attention demanding.

Some capacity theorists argue there is a single, general-purpose capacity for attention (Kahneman, 1973). Resources⁴ reside within this single undifferentiated reservoir, which are voluntarily allocated in graded quantity to *any* act or stage of processing dictated by a higher-level executive program. One important aspect of Kahneman's (1973) model is his contention that resource allocation depends on the state of the organism (e.g., level of physiological arousal). Since Kahneman views attention as a 'pool of effort' placing demand on mental resources, he suggests that an organism's level of excitability (i.e., arousal level) has a distinct impact on the availability of resources. If, for example, the arousal level of an individual is low, there will be a decrease in available attentional capacity when compared to resource availability at higher states of arousal. As a result, Kahneman often uses the terms capacity, attention, and effort interchangeably.

Other capacity theorists have argued that attention should not be conceptualized as a single resource. Rather, attention should be viewed as a multiple pool of resources, each with its own capacity and capability to handle certain types of information (i.e., structure specific resources). According to this perspective, task interference occurs because two tasks call upon the same reservoir of resources. If there is no overlap in the resources demanded by either task, then the individual should be able to perform both tasks in parallel. As such, attention can be simultaneously devoted to separate stages of processing (e.g., Allport, Antonis, & Reynolds, 1972; Navon & Gopher, 1979; Wickens, 1980, 1984). To lend viability to multiple resource theory, an important direction has been to establish the exact nature of these proposed resource pools. The most extensive work in this area has been conducted by Wickens (1980, 1984) who suggests that the structural composition of resource reservoirs can be characterized on at least four dimensions: (1) stimulus characteristics (visual and auditory), (2) internal codes (visual and verbal), (3) response characteristics (manual and speech), and (4) levels of processing (shallow and deep). Multiple resource theory then, holds important

⁴ Within the literature, the term 'resource' has been defined in a number of ways. For example, Norman and Bobrow (1975) have defined resources to include "processing effort, the various forms of memory capacity, and communication channels" (p. 45), while others have identified resources as "units, channels, and facilities" (Navon & Gopher, 1979, p. 233).

practical implications in such fields as human factors. For example, when designing a system, it suggests that a human factors engineer should contemplate a design that minimizes the overlap of demands on common resources for tasks that will be performed concurrently. Such consideration serves to not only increase the information processing capabilities of the human operator, but also reduces the potential for human error by distributing demands across resources (Wickens, 1984).

From this perspective, attention is defined in terms of the interference between concomitant performance of two tasks. Using experimental protocols designed to overload the system, resultant patterns of interference provides investigators insight into understanding the nature of underlying control mechanisms of different tasks, as well as a general indication of the attentional capacity available to different individuals for processing information (Abernethy, 1993).

Assessing Attention Demands

Following the logic presented in the preceding section, one way to assess attention demands of a given task, is to engage participants in the simultaneous performance of two tasks – a basic task, which is referred to as the primary task, and a secondary task. The primary task is the task for which attention demands are assessed, while performance on the secondary task is used to derive attention demands required by the primary task. An important methodological constraint of this approach, referred to as the secondary-task paradigm⁵, is to employ an instructional set, which requires participants to give attentional priority to the primary task so that a given level of performance can be maintained during concurrent performance of the subsidiary task (Ogden, Levine, & Eisner, 1979). Performance measures obtained in the dual-task condition are then compared to levels of performance obtained when the secondary task is performed in isolation (i.e., under

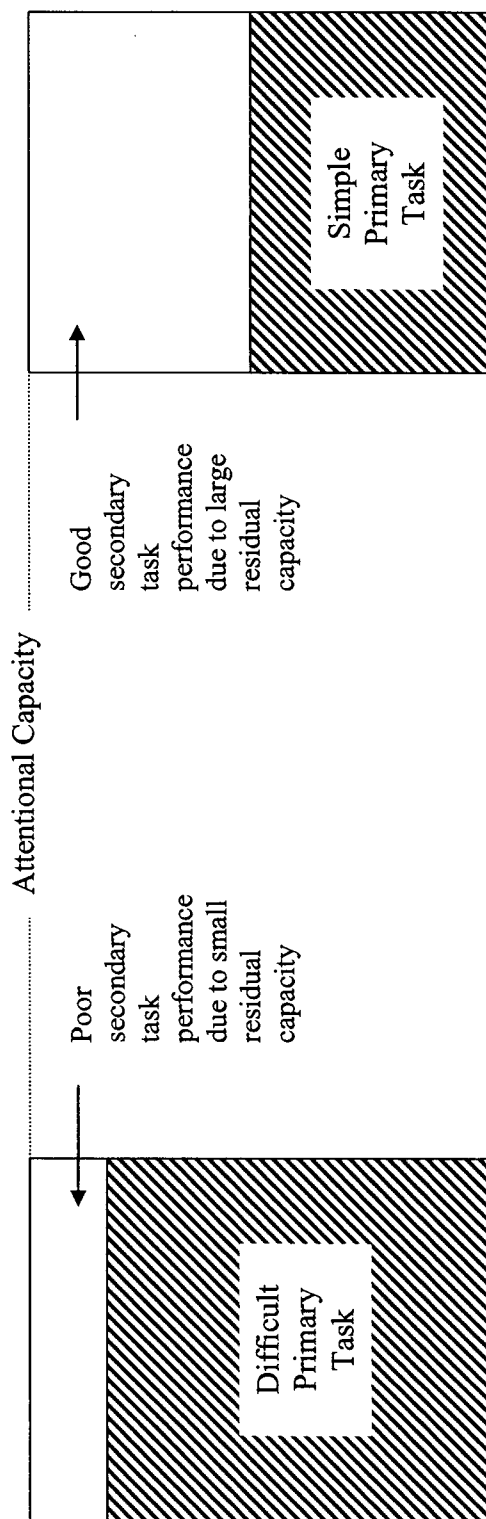
⁵ The terms secondary-task and dual-task paradigms have often been used interchangeably within the majority of published literature (Abernethy, 1988; 1993). However, Ogden et al. (1979) have made a distinction between the terms based on the use of different instructional sets. Participants are instructed to either afford processing priority to the primary task or instructed to perform both tasks to the best of their capability. As such, it is recommended that these instructional sets be referred to as secondary-task and dual-task paradigms, respectively.

control conditions). The difference between the two levels of performance is taken as an index of the attention demands imposed by the primary task. Implicit within this theoretical approach is the notion that the secondary task does not interfere in the performance of the primary task.

If one assumes (1) the existence of limited pool (or pools) of processing resources, and (2) the use of an instructional set that allocates processing priority to the primary task, it is postulated that secondary-task performance is a direct reflection of the amount of “free attentional space” or “residual processing capacity” that remains for secondary task execution after the demands of the primary task have been met. If poor performance (relative to control levels) is displayed on secondary activity, it is hypothesized that a large proportion of information-processing capacity has been allocated to the primary task so that an acceptable level of performance can be maintained. In contrast, if secondary task performance remains relatively unchanged from control levels, it is proposed that only a small proportion of information-processing capacity has been allocated to the primary task (Figure A2). As such, poor performance is expected to accompany relatively difficult primary tasks, which demand a substantial proportion of attentional capacity for task execution; while, good secondary task performance is expected to be associated with more simple primary tasks, which place little demand on the performer’s limited processing capacity.

To determine if attentional capacity is required throughout the performance of a motor skill, researchers typically employ a secondary task that is continuous in nature. For example, participants could be required to count backwards in threes while trying to produce a criterion bimanual coordination pattern (see Hodges & Lee, 1999). In contrast, a discrete probe technique may be used if the researcher is interested in examining the attention demands required at a specific point in time or by a specific component of the motor task. The probe technique is illustrated in Experiments 1 – 5 of this dissertation. While performing a bimanual coordination task, a computer generated “beep” sounded. As soon as the individual detected the beep, (s)he was required to respond as quickly as possible by providing a vocal response into a microphone. Further discussion of this technique is now presented.

Figure A2. Theoretical assumptions underlying secondary-task methodology (adapted from Abernethy, 1988, 1993).



Probe Reaction Time Technique (Probe-RT). Although a diverse range of secondary tasks has been employed (see Ogden et al., 1979, for a review), probe reaction time (Probe-RT) measurements are prevalently used to determine attentional fluctuations during the execution of a particular primary task. The premise of this technique is to present a stimulus (probe) while carrying out the required primary movement. At the onset of a probe, the participant is instructed to respond as quickly as possible to the stimulus (e.g., by pressing or depressing a telegraph key) while simultaneously maintaining primary task performance. If primary performance is the same on trials with and without the probe, then it is assumed that any delay in probe reaction time (relative to control levels) reflects the processing requirements of the primary task. The attention demands of component processes of the primary task are inferred by having the onset of the probe occur at different times within the movement (e.g., probe onset is simultaneous with the start of the movement). When a particular component of the task elicits a delay in RT, that process is said to be attention demanding. If there is no delay in RT it is assumed that attention is a minimal requirement or may not be needed at all for the execution of that particular task component. This line of investigation has sought to answer such questions as: Is attention necessary for response initiation and/or movement termination? Does the precision requirement of a movement task affect its attention demand? (Stelmach & Larish, 1980).

Overall, empirical work using probe-RT measures suggests that movement control requires attention. Moreover, the relative degree of attentional involvement changes systematically throughout the execution of the movement. For example, in an early study examining the execution of a simple reaching movement, Posner & Keele (1969) found that probe-RT was always larger than baseline RT. This suggests that the linear positioning movement demanded attention. Furthermore, the shape of the curve relating RT to probe position was U-shaped. Attention demands were markedly elevated at the initiation of the movement, reduced in the middle portion, and then increased towards movement termination in an attempt to achieve precise positioning on the target. Posner and Keele support this latter interpretation by demonstrating that probe-RT increased when precision of the task

increased (also see Ells, 1973; Salmoni, Sullivan, & Starkes, 1976, for further investigations examining simple linear positioning movements).

More recently, the probe technique has been used to assess the time course of attentional fluctuations in a number of real-world sport tasks, as well as laboratory simulations of these tasks. Examples include: ball-tracking (Nettleton, 1979), simple catching (Populin, Rose, & Heath, 1990; Starkes, 1987); service reception in tennis and volleyball; as well as sprinting and hurdle running (Castiello & Umiltà, 1988), horseshoe pitching (Prezuhý & Etnier, 2001); rock climbing (Bourdin, Nougier, & Teasdale, 1997; Bourdin, Teasdale, & Nougier, 1998); and pistol shooting (Rose & Christina, 1990). In a number of these activities, the observed pattern of attentional demands were similar to those revealed in the control of simple linear aiming movements (e.g., Posner & Keele, 1969). Using a laboratory coincident-anticipation timing task, for example, Nettleton (1979) found the greatest allocation of attention to the early and final stages of an approaching stimulus, rather than to the middle 'less attention demanding' portion of its approach. In this investigation, a coincident-anticipation task was employed to replicate attentional demands of tasks requiring ball-tracking skills (e.g., soccer, field hockey). In consideration of more 'real-world' assessments, Prezuhý and Etnier (2001) asked individuals to pitch horseshoes to target stakes of varying difficulty. Results revealed that horseshoe pitchers allocated a greater portion of attentional resources to the initiation of the pitch and the point just prior to the release of the horseshoe, than to the full extension on the backswing. When examining sprinters executing a 100 m dash, Castiello and Umiltà (1988) demonstrated delayed response latencies of probe-RT at the beginning and at the end of the race. An interpretation of the results suggests that the beginning portion of the race involves the start, whereby attention must be devoted towards detection of the start signal and preparation of the response. However, the performer must also allocate attentional resources to the end portion of the race to monitor distance to the finish line, the relative positions of the opponents, as well as the final thrust to the finish line.

In contrast, a number of studies have revealed attentional patterns unique to the aforementioned findings. For hurdlers, Castiello and Umiltà (1988) found elevated

probe-RTs throughout the middle of the race, particularly when the athlete was about to negotiate the first hurdle. In the same series of investigations, Castiello and Umiltà also revealed task-specific attentional fluctuations for service reception in tennis and volleyball. In both activities, attentional demands were greatest when the ball hit the court (just prior to performing the return in tennis) or after crossing the net (just prior to hitting the ball in volleyball). Contrarily, the least demanding conditions for service reception in tennis and volleyball occurred at the opponent's serve and when the ball was above the net. Work by Rose and Christina (1990) has also revealed a unique attentional time course for shooting. When examining the distribution of attention across the aiming phase of a discrete pistol shot, it was found that probe-RT increased when the auditory probe was presented at a time more proximal to the time of the shot. Given that probe-RT increased in a near linear fashion, Rose and Christina concluded that the demands on attentional capacity increased as the actual time of the shot approached.

Empirical work using the probe-RT technique not only demonstrates that attentional involvement changes systematically throughout the execution of a movement, but also reveals a unique array of attentional patterns. However, further examination is needed to establish a more extensive database regarding the time course of attention demands within the execution of a motor task (Abernethy, 1993). Although limited, current empirical work suggests that certain tasks may display common patterns of attention. In particular, are those tasks, which interact with the environment in a comparable manner. Prezuhy and Etnier (2001) argue that a general attention pattern may exist for different classifications of tasks. For example, projection-type tasks (horseshoe pitching, bowling, throwing) may display one kind of attentional demand profile, while reception-type tasks (hitting a pitched ball, receiving a serve in tennis or volleyball) may exhibit another. This line of inquiry is clearly warranted from a motor learning perspective in that it has the potential to enhance instructional techniques and ultimately improve performance.

Summary

Any model that seeks to describe human skill acquisition must take into consideration the mediating influences of attention. One approach has been to examine the nature of human performance with a direct emphasis on discovering the attentional limitations of the processing system. Specifically, a prominent line of investigation has been to examine the limitations on the amount of information an organism can select for processing at any given period of time. Coined as the study of divided attention, researchers seek out an explanation for why the human system is seemingly able to perform two tasks concurrently, or contrarily, why the performance of one task interferes with the simultaneous performance of another task in certain movement situations. One of the most widely accepted theoretical explanations for dual-task interference is the one proposed by resource or capacity-sharing models. These models postulate the existence of a limited pool (or pools) of processing capacity, which can be partitioned between two tasks. If the concurrent tasks tap into the same resources and joint demands exceed the total capacity of available resources, a dual-task decrement incurs in one, or both of the simultaneously performed tasks. Moreover, to examine processing capacity demanded by a task (i.e., attention demands), a basic secondary task paradigm is employed, which requires the simultaneous performance of two tasks – a primary task, for which attention demands are assessed, and a secondary task, from which attention demands of the primary task are derived. Empirical work using probe-RT measures suggests that attentional demands change systematically throughout the execution of a movement and the resulting pattern is specific to the particular task of interest.

The Relation between Attention and Automaticity

The link between automaticity and skilled behaviour is not a new concept and is well entrenched within academic psychology. For example, Adams (1987) has traced the notion of automaticity back to the writings of Bain (1868) and Spencer (1881). Bain (1868) is of particular interest in that he discussed the principle of contiguous association whereby movements could be linked together in trains and

made to succeed each other. Using such examples as the sequence of acts in eating, the articulation of speech, the playing of the pianoforte, and the acquisition of the diagonal step in a military walk, Bain suggested that succession of regulated acts occur with mechanical coherence and certainty because they have been made to succeed each other a great many times. In the acquisition of articulate speech, Bain stated that, "every letter stands in need of an adjustment of tongue, jaws, and lips, difficult at first, but at last so easy that we do not know that we are performing a complicated act" (p. 331). Furthermore, he suggested that the effect (or 'feeling') produced at the end of each movement is a link in the transition to the next action. Early in learning, this notion of 'feeling' guides an individual's mechanical effort until the movements are fixed in a sequence, operating independently of any guidance. This last stage is epitomized to represent the highest perfection of mechanical acquirement.

Inherent within Bain's writings, was an anticipated preamble of what was yet to come. In James' (1890) *Principles of Psychology*, an entire chapter was dedicated to the notion of 'habit', where automaticity was discussed in terms of the response-chaining hypothesis. According to this hypothesis, each segment of a movement produces response-produced feedback. The feedback from one movement segment becomes associated to the next movement sequence by a habit connection, and acts as a stimulus for the next movement in the sequence. With respect to acquisition, James suggested that a voluntary act has to be guided by "idea, perception, and volition, throughout its whole course" (p. 115). However, once a habit connection has been formed, movements can be run off as smooth serial actions. In a habitual action, "mere sensation is a sufficient guide and the upper regions of the brain and mind are set comparatively free habit diminishes the conscious attention with which our acts are performed" (p. 115-116 & p. 114, respectively). Although other psychologists had acknowledged the concept of automaticity in their writings (e.g., Bain, 1868), James popularised the response-chaining hypothesis. As such, the idea that a shift from controlled to automatic processing occurs over extensive practice has usually been attributed to the 1890 writings of James (see Adams, 1984, 1987).

At the end of the 19th Century, Bryan and Harter published two seminal papers, which examined the acquisition of skill in telegraphy (Bryan & Harter, 1897, 1899). The work of Bryan and Harter is considered 'seminal' in that many of the ideas presented within these two papers sparked an interest in the study of motor expertise, serving as an impetus for theorizing and research within the area of motor learning throughout the latter half of this century. According to Lee and Swinnen (1993), Bryan and Harter's work opened the door for research in three distinct areas: the examination of expertise in terms of systematic differences in performance variation; the nature of change in acquisition, as well as the development of automaticity in expert performance. The latter concept of automaticity was perhaps, the most important legacy of Bryan and Harter and has remained a consistent theme within present-day theories and research pertaining to the acquisition of skilled behaviour (see Lee & Swinnen, 1993).

According to Bryan and Harter, acquiring expert levels of motor performance depends on the attainment of higher-order habits, and therefore, automaticity is hierarchical in nature. Higher-order elements of the task cannot be attended to until lower aspects of the task are performed relatively attention free. In their words, "only when all the necessary habits, high and low, have become automatic, does one rise into the freedom and the speed of the expert" (1899, p. 357). Stated differently, "there is no freedom except through automatism" (1899, p. 369).

Unfortunately, interest in automaticity waned with the onslaught of behaviourism, and did not reappear until Miller, Galanter, and Pribram's (1960) publication of *Plans and the Structure of Behavior* (Lee & Swinnen, 1993). Within this piece of work, Miller et al. viewed skilled behaviour as a function of a plan that becomes habitual in nature through the process of overlearning. More specifically, Miller et al. suggested that early in acquisition, the beginner formulates a plan to guide gross actions for the control of a sequence of skilled actions. In order to execute the plan as a smooth and controlled behavioural unit, the individual must identify interposed elements that produce the skill. Eventually, the plan becomes almost innate (or instinctive) as it develops the qualities of automatic behaviour (e.g., inflexibility, resistance to change, involuntary responses). Simply stated, Miller et al.

suggested that automaticity provides the individual a method of manufacturing his own instincts whereby habits and skills are viewed as plans that have become automatic.

Emergence of the cognitive revolution in the 1950s and the 1960s facilitated debate on the relation between attention and automaticity. At the outset, research focused on selective attention and the fate of unattended material (Logan, Taylor, & Etherton, 1999), where the purpose of empirical investigations was to determine at what level a parallel system, unlimited in capacity, narrowed to a serial system, limited in capacity. The former implying the use of preattentive or automatic processes, while the latter involving processes that require attention.

Early selection theorists argued that information entered the cognitive system in parallel, but only low-level perceptual features were processed preattentively. Any further analysis at the semantic level was postulated to demand attention (e.g., Broadbent, 1958). In contrast, late selection theorists argued that limitations in the system occurred later on in processing, after a message has been processed to the extent that its relationship to other messages is determined. These models proposed the notion of a 'smart filter' where selectivity is based on highly complex discriminations occurring beyond the stimulus level and after at least some degree of preattentive semantic analysis. From this perspective, attention is required at the level of response selection since all incoming signals have been processed prior to this stage (e.g., Deutsch & Deutsch, 1963). Inherent within both early- and late-selection theories is the idea that automatic processes are independent of attention (Logan et al., 1999).

In the 1970s, interest shifted from the investigation of selective attention to the study of divided attention. Embedded within this new dominant paradigm was the notion that automaticity was a learned phenomenon. Therefore, an interest in the study of behaviour under conditions of prolonged practice emerged within the psychological literature.

Automaticity as a Learned Phenomena

One of the most significant contributions to the area during this time period was the work of Schneider and Shiffrin (Schneider & Shiffrin, 1977; Shiffrin and Schneider, 1977), who studied the nature of automatic processing by asking such questions as: Is automatic processing qualitatively different from effortful processing? What kinds of processes become automatic? (Hirst, 1986). In their work, Schneider and Shiffrin employed a basic visual search and detection paradigm, in which the participant was asked to search displays for target items. The individual was first shown a memory set of one (or more) alphanumeric character(s), and then asked to identify whether the item (or any member of the memory set) appeared in a subsequent frame, referred to as the visual display set. A presented memory set item was called a target, while the other presented stimuli were always referred to as distractors. The task could be made extremely easy (i.e., the participant was required to memorize only one item and received only one item in the visual display); or the task could be made difficult (i.e., the participant was given four items to memorize as well as four items in the visual display). Participants were also examined under two different mapping conditions referred to as consistent mapping (CM) and varied mapping (VM). Consistent mapping (CM) was used to denote those conditions where items in both the memory and visual display sets never changed across trials. That is, only numbers were used as items in the memory set and only consonants were used as distractors in the visual display set (or vice-versa). The latter condition of varied mapping (VM) involved the intermixing of memory-set and distractor items, as well as a random change in roles across trials. For example, in the VM conditions both numbers and consonants were used as items in a manner such that a target on one trial could be a distractor on another trial, and vice-versa. This method of investigation led Schneider and Shiffrin to a number of important findings. After extensive training under conditions of CM, performance was found to be largely unaffected by load (defined as a product of memory-set size and visual display size). With prolonged practice, participants displayed fast reaction times in all conditions of load, and target detection accuracy was high even when frames were shown to the individual at a rapid rate of display.

Furthermore, participants were able to carry on a conversation while performing the task, which suggests that the CM condition became easy with practice and demanded little attention or effort from the performer. However, in conditions of VM, performance did not improve and remained relatively unchanged even after months of practice. In the VM conditions, participants reported that the task was rather arduous and commented that it demanded a conscious allocation of attention on their part. Since effects on both the memory-set size and display-set size were twice as large on trials when there was no match between any of the memory items and any of the visual display items (i.e., negative trials) Schneider and Shiffrin concluded that participants were using serial comparison to elicit a response. That is, participants were comparing each item in the visual display against each item in the memory set to find a match. Such a comparison can only be made serially and at a limited rate. According to Schneider and Shiffrin, the process of serial comparison is an example of a controlled mode of processing. In contrast, controlled comparison is not needed to locate the target after prolonged practice in CM conditions. Rather, it was proposed that target detection was attributed to the use of automatic processes operating independently and in parallel as a result of training. Interestingly, Schneider and Shiffrin also examined performance when task demands were reversed after substantial practice using consistent mapping. In the first 2100 trials of practice, participants received a memory set, which could only consist of consonants from B to L, and a visual display set consisting only of consonants from Q to Z (or vice-versa). After 2100 trials under consistent mapping, participants' accuracy for target detection increased from an initial 55% to a detection rate greater than 80%. However, this initial set of trials was then followed by an additional 2400 trials of consistent mapping where the composition of each set was reversed (i.e., memory set = consonants Q to Z; visual display set = consonants B to L, and vice-versa). After the reversal, detection accuracy fell to a mere 30% and did not achieve initial levels of performance (i.e., 55% detection accuracy) for another 1000 trials. According to Schneider and Shiffrin, this occurred because automatic processes developed in the first set of acquisition trials continued to interfere with

performance in the second set of trials, despite a participant's awareness that the requirements of the task had changed.

These findings led Schneider and Shiffrin to postulate that there are two distinct modes of processing, which take the form of controlled search and automatic processing. Controlled processing is defined as a slow, generally serial, effortful, subject-controlled processing mode, which requires active attention to deal with novel and inconsistent information. It is capacity-limited as a result of short-term memory constraints (e.g., limited-comparison rate) and is strongly dependent on load. Furthermore, control processes can be adopted rather quickly, without extensive training, may be readily altered or even reversed by the individual, and can be used to control the flow of information within and between levels, as well as the control of information between short-term and long-term memory stores. Most specifically, control processes may be used to transfer automatic sequences and general information to long-term memory stores. According to Schneider and Shiffrin, examples of control processes include maintenance or rote rehearsal, coding rehearsal, serial and long-term memory search, as well as strategy search and decision-making of all types. In contrast, automatic processing is defined as a fast, fairly effortless process that operates in parallel, does not require attention, and is not hindered by the capacity limitations of short-term memory or affected by load. That is, processing resources are not required by the system. Furthermore, automatic processes are not under direct subject control in that once initiated, all automatic processes run to completion automatically. Acquiring automatic processes requires considerable and extensive training to develop, and once acquired becomes very difficult to control, modify, or suppress.

A second aspect of Schneider and Shiffrin's automatic and controlled processing framework regards the development of automaticity. According to this theoretical perspective, an environment, which provides the individual an opportunity to respond to a stimulus in a consistent manner, should lead to the development of automatic processes under conditions of extended practice. In contrast, automatic processes should not develop in conditions where stimulus processing is not consistent, even when the individual is exposed to extended practice.

The notion of controlled and automatic processing is apparent in classic theories of motor skill acquisition such as Fitts and Posner's (1967) three phase framework. For example, the qualitative differences associated with each phase of acquisition are postulated to result from a gradual reduction of the amount of cognitive activity associated with the response. Therefore, performance in the cognitive phase is attributed to controlled processing. In the associative phase, performance involves both controlled and automatic processes for task execution, while performance in the autonomous phase is mainly attributed to automatic processing.

Limitations of Current Theory and Empirical Work

According to capacity sharing theories, extended practice on a task leads to 'automaticity'. From this perspective, automaticity is defined as processing without attention, whereby practiced operations no longer impose demands on a system's resources for task execution. Most simply, practice permits the development of the ability to bypass attention (e.g., LaBerge & Samuels, 1974; Shiffrin & Schneider, 1977) with the underlying assumption that more practice on a task leads to more automaticity (Brown & Bennett, 2002).

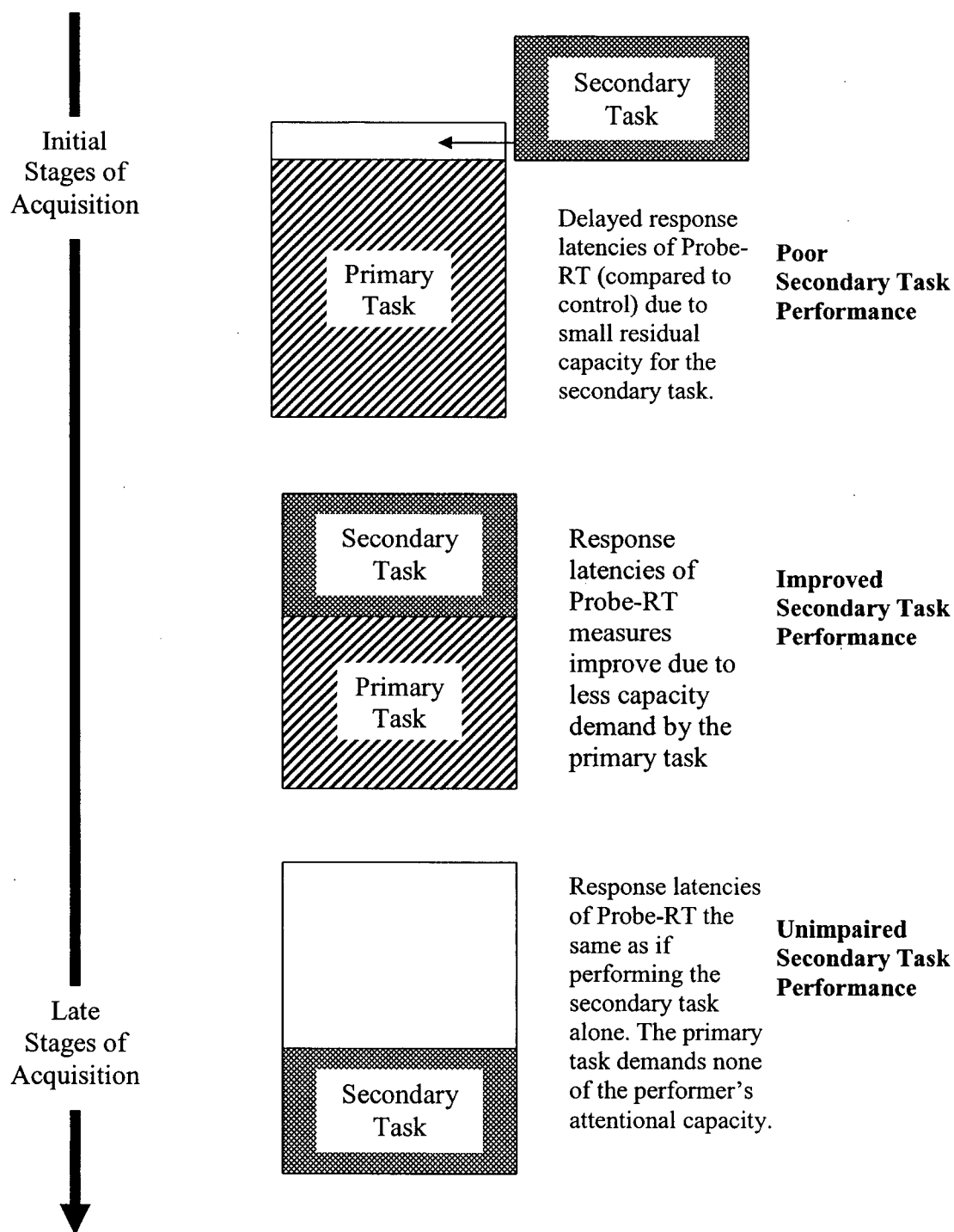
To assess levels of automaticity in an experimental setting, the classic measure of probe-RT is often employed. At early stages of learning, it is postulated that subsidiary task performance will be relatively poor (e.g., response latencies in probe-RT > baseline RT). This supposition is based on the idea that primary task performance demands a large portion of the learner's processing capacity, leaving only a small amount of free attentional space for processing the demands of the secondary task. However, after an extended period of task-specific practice, primary task performance improves and the demand for a large proportion of the performer's limited processing capacity diminishes. At this point, it is postulated that relatively unimpaired secondary task performance emerges. Good secondary performance is assumed to parallel a primary task that demands little of the performer's limited processing capacity, which leaves enough residual processing capability for the execution of the secondary task. Moreover, when the primary and secondary task

can be performed as well simultaneously as individually, a single-to-dual task decrement of zero, automaticity of the primary task is assumed (e.g., probe-RT = baseline RT). Available processing capacity previously required to obtain maximal performance is now diminished and primary task execution requires little or none of the performer's attentional capacity (Figure A3).

In practice, however, it is generally accepted that complete elimination of dual-task interference is not necessary to demonstrate automatic processing. Rather, evidence of automaticity is taken whenever there is a significant decrease in dual-task interference following practice of a task (Brown & Bennett, 2002). Moreover, studies examining the acquisition of novel motor tasks rarely include periods of prolonged training; yet, traditional theories of skill acquisition assume that learning progresses in phases that can be differentiated on the basis of the cognitive activity associated with the production of the response (Adams, 1971; Fitts & Posner, 1967). Although this notion has been readily accepted within the motor learning literature, Adams (1987) has poignantly pointed out that there is "no evidence of a shift from controlled to automatic processing for motor behaviour" (p. 66). One reason for this lack of empirical foundation is that investigating the acquisition of a complex motor task mandates extended observation before an individual begins to approximate high degrees of task proficiency. Therefore, the amount of practice trials typically employed in learning studies have been limited, constraining investigation to the early acquisition stages of the learning process (see Adams, 1987 for a review).

In recent years, researchers have begun questioning whether elimination of dual-task interference is actually achievable, as suggested in the basic theoretical tenets of a capacity perspective (Pashler, 1998), even after extended periods of practice. In contrast, even well practised motor tasks operating at consistently high levels of excellence are postulated to demand attention. Therefore, a fundamental research question is to examine the effects of extended practice on attention demands and dual-task interference of a complex motor task. This idea was examined in the present series of investigations. The primary purpose of which, was

Figure A3. The Secondary-task paradigm. Theoretical assumptions underlying the achievement of automaticity using the probe-RT technique.



to investigate the effects of practice on attention demands and dual-task interference across the extended acquisition of a novel motor task.

Summary

Two distinct operating modes have been identified to describe human information processing: a controlled mode of processing requiring active attention, and an automatic mode of processing operating without the use of attention. In strictest terms then, automaticity is described as a gradual withdrawal of attention over practice. Empirical investigations using a secondary-task paradigm support the notion that the concomitant performance of two or more tasks can be improved with practice, and that this capability may be a necessary component of expert levels of performance. However, researchers have recently begun questioning whether elimination of dual-task interference is actually achievable, even after extended periods of practice.

SECTION THREE

Skill Acquisition from a Dynamic Pattern Perspective

In the seventies, the information-processing model was the dominant approach driving human movement research. Within this perspective, motor tasks were predominately used as a means to assess the duration of internal cognitive processes using such measures as reaction time. However, a difficulty of this perspective has been in explaining how the human motor apparatus is capable of organizing motor output to produce smooth and coordinated movement. This question became a fundamental issue within recent approaches to human movement research because of a concern for understanding the degrees of freedom problem.

A degree of freedom refers to an independent state within the human body. To produce a coordinated action, the concomitant control of many independent states is required. However, according to the insights of Bernstein (1967), it is unreasonable to suggest that the central nervous system is capable of cognitively controlling all the degrees of freedom required to produce a coordinated action. For example, consider the human body in terms of joints, muscles, and motor units. If a joint is capable of moving independently in one direction, it possesses one degree of freedom; while the ability to move in two directions, denotes two degrees of freedom. Thus, to move the arm, it is estimated that seven degrees of freedom must be controlled (shoulder joint = 3; elbow joint = 1; radio-ulnar joint = 1; wrist joint = 2). However, attached to and acting on each joint are muscles, each of which possesses additional degrees of freedom to manage. To move the arm now, a minimum of 26 more degrees of freedom must also be controlled (shoulder joint = 10; elbow joint = 6; radio-ulnar joint = 4; wrist joint = 6). This estimated number increases exponentially if motor units are also considered (see Turvey et al., 1982 for discussion of the various units of control).

In consideration of this overwhelming problem, theorists have suggested that too many individual units exist for a system to regulate separately. Hence, the degrees of freedom problem refers to the impossible situation that unfolds for our central nervous system if it had to control all the ways a system is capable of moving

through conscious decision alone (Schmidt, 1988). Rather than executive processing, Bernstein suggested that groups of muscles spanning more than one joint operate as functional task-specific units called synergies or coordinative structures, which are innate or develop through practice. For example, when observing the concomitant performance of aiming movements to targets of varying size, Kelso, Southard, and Goodman (1979) demonstrated simultaneous initiation and termination of limb movements regardless of the different index of difficulty for each task. The limb moving to the larger (or easier) target slowed down, while the limb moving to the smaller (more difficult) target increased in speed. Contrary to Fitts Law⁶, these findings suggest that the upper limbs naturally act as a single unit when they are required to simultaneously achieve an action goal. Functional coupling between the limbs is advantageous to the performer because the task is made simpler by reducing the number of elements that need to be controlled.

In summary, the degrees of freedom problem was a critical concept, which focused on examining how the individual coordinates and controls a complex motor system. Instead of a predominant focus on simple movements, a transition occurred to the examination of more complex motor skills (see Swinnen & Carson, 2003 for a historical review of interlimb coordination). In an attempt to alleviate the degrees of freedom problem, an alternative paradigm to human information-processing emerged within the motor behaviour domain. This new paradigm, referred to as dynamical pattern theory, was motivated by principles of synergetics, a physical theory of spontaneous self-organization and pattern formation in complex, nonequilibrium systems (Smith & Thelan, 1993). Using mathematical tools from nonlinear dynamics, the strength of this approach is that it affords the researcher an opportunity to examine how patterns of coordination change as a function of dynamic forces acting on and within the motor system over time.

⁶ Fitts Law is a mathematical equation, which predicts movement time for a target situation requiring both speed and accuracy. It implies an inverse relationship between the difficulty of a movement and the speed it is performed at. If a target is decreased in size or the distance to a target is increased, the task becomes more difficult. Therefore, when both arms are required to aim to targets of different sizes, Fitts Law would predict different movement times for each limb (see Schmidt & Lee, 1999).

Motor Dynamics: Fundamental Concepts and Terminology

The human is a highly complex system comprised of many components at any given level of analysis (e.g., molecular, neuromuscular, psychological). Rather than act as independent elements, particular configurations (or collective actions) spontaneously form to govern the behaviour of a system. Such an action denotes the emergence of a coordination pattern, which is defined as an observable, reproducible, and stable relationship amongst the components of the biological system (Zanone & Kelso, 1994).

In a nonequilibrium system, a spontaneous change in a coordination pattern occurs because of a change in an outside variable, called a control parameter. Manipulating or changing a control parameter influences the stability of a pattern. When changes in the control parameter bring the system to a critical threshold, a spontaneous change in the coordination pattern will occur such that the system tends toward, or relaxes to, preferred behavioural or attractor states (Schmidt & Fitzpatrick, 1996). This spontaneous change, also referred to as a phase transition, signifies a qualitative modification of the system's underlying coordination dynamics (Zanone & Kelso, 1994). In essence, a control parameter pushes a system through the collective states (or patterns) of a system, without dictating the coordination pattern that is to be produced. As Wallace (1996) has stated, "changes in the control parameter allow the system to self-organize and produce patterns with differing degrees of stability" (p. 160). To describe emerging patterns of a system, researchers use functionally specific order parameters (or collective variables) that are directly measurable. For example, the collective variable of relative phase (RP) is used to quantify rhythmic, multilimb coordination movements. The strength of this measure is that it captures the essential properties of pattern formation, stability, and change observed in a coordination task (Zanone, Monno, Temprado, & Laurent, 2001).

To illustrate the above ideas, image yourself walking on a treadmill. Suppose the speed of the treadmill begins to steadily increase. Speed is an outside force imposed on the system and is therefore the control parameter. If the speed of the treadmill continues to increase, it will eventually become too fast to execute a

walking pattern. Consequently, you will have to change to a running pattern. This transition in pattern occurs naturally (spontaneously, without thought) and takes place when some critical speed is reached. According to dynamical pattern theory, the transition from walking to running occurred because the walking pattern became more unstable and variable as the speed of the treadmill increased. Therefore, the system switched to the running pattern to regain stability at the increased speed (example from Sherwood, 2000). Similar transitions in gait have also been observed in quadruped locomotion. For example, when increasing the speed of a treadmill, a four-legged animal will spontaneously shift from a walk to a trot, and finally, to a gallop. One catalyst for changing to a new gait may be energy efficiency. Increasing the speed of a gait pattern beyond a critical level results in an energy cost. Therefore, making a transition to a new gait increases the efficiency of the system as well as its stability (see the work of Hoyt & Taylor, 1981 for discussion on speed selection and transitions in gait on horses).

In humans, the study of the principles governing interlimb coordination was largely pioneered by Kelso and colleagues (e.g., Haken, Kelso, & Bunz, 1985; Kelso Scholz, & Schöner, 1986; Scholz, Kelso, & Schöner, 1987; Schöner & Kelso, 1988; Schöner, Zanone, & Kelso, 1992). Currently, there exists a wealth of empirical support demonstrating that when performing cyclical (or oscillatory) bimanual limb movements at low frequencies, the human motor system displays two inherently stable patterns of coordination - a strong symmetrical in-phase limb relationship and a somewhat weaker asymmetrical anti-phase limb relationship (e.g., original experiments conducted by Kelso, 1981, 1984). With respect to upper limb movements, in-phase coordination may be described as an attraction towards synchrony or defined as the simultaneous flexion and extension of homologous muscle groups. When an in-phase pattern is displayed, the limbs coordinate so that they are in the same place in the cycle at the same time. In contrast, anti-phase coordination is characterized as a tendency towards alternation and occurs when the flexion and extension of homologous muscles work in an alternating fashion, much like the operation of a pair of windshield wipers in the rain. Therefore, when

the limbs coordinate in the opposite place in the cycle at the same time, an anti-phase behavioural tendency is demonstrated.

To quantitatively differentiate between these two patterns, a relative phase measure can be calculated for each. More specifically, the movement of one limb from maximal flexion to maximal extension and back again, represents one complete cycle (an angular coordinate of 360°). During a cycle, the position of each limb corresponds to a phase value at any given point. Subsequently, a relative phase value for any common point in the cycle is obtained by calculating the difference in phase values for each limb from a determined starting point. For example, if the limbs move in synchrony from maximal flexion to maximal extension, and then back to maximal flexion, the relative phasing between the two limbs is 0° , representing an in-phase pattern of coordination. In contrast, if the starting position for one limb is at a point of maximal flexion (0°), and the other limb starts at a point of maximal extension (180°), the relative phasing is 180° if this limb relationship is maintained for the duration of the cycle. This represents an anti-phase pattern of coordination (Wallace, 1996). In short, relative phase refers to the spatial and temporal difference between the limbs at any point in time.

In dynamical language, in- and anti-phase are considered to be differentially stable attractor states (Kelso, 1984). When movement frequency is progressively scaled beyond a certain critical region, anti-phase coordination loses stability and a phase transition occurs towards the in-phase attractor. That is, a linear increase in movement speed leads to a change in behaviour that is abrupt and nonlinear. Interestingly, the in-phase pattern of coordination does not break down at a higher frequency of oscillation. Rather, it remains the preferred coordination mode even when cycling frequency is reduced. This phenomenon is referred to as system hysteresis. Based on such findings, in-phase coordination is considered to be the stronger, more stable attractor basin when compared to anti-phase coordination. One explanation that has been provided for the differential stability of in-phase and anti-phase coordination is direction, whereby individuals tend to exhibit a preference for homologous directional coordinations (Carson, Goodman, Kelso, & Elliott, 1995; Kelso & Jeka, 1992).

In-phase and anti-phase behavioural tendencies are referred to as the intrinsic dynamics of a system. Stated differently, the intrinsic dynamics of a system can be viewed as the dynamics of the order parameter when environmental information is absent (Wallace, 1996). These pre-existing or preferred patterns of coordination are similar across individuals and performed skillfully without practice. In the words of Kelso (1995), the intrinsic dynamics of a system represents “relatively autonomous coordination tendencies that exist before learning something new” (p. 163). Such an approach brings with it the assumption that the initial state of an organism is not tabula rasa (blank state) or a disordered random network, rather it is organized or ordered (Kelso, 1995).

Dynamic Modelling of Interlimb Rhythmic Coordination

In the most parsimonious of definitions, a dynamical system is simply “an equation or set of equations stipulating the evolution in time of some variable, x ” (Kelso, 1995, p. 53). In regards to bimanual coordination, research interest lies in the temporal evolution of the order variable relative phase. That is, how does relative phase change from one moment to the next as the control parameter of cycling frequency is varied (Kelso, 1995)?

In summary (see preceding section), empirical research (originally conducted by Kelso 1981, 1984) yields three important observations into the dynamical evolution of relative phase. These are:

- (1) Two stable behavioural patterns (in- and anti-phase) exist at low oscillation frequencies (i.e., bistability of the system at certain frequencies).
- (2) When scaled beyond a critical region, anti-phase coordination becomes unstable and a transition occurs to an in-phase mode of coordination (i.e., an observed bifurcation from bistability to monostability of the system at a critical frequency).
- (3) When cycling frequency is reduced, a tendency to maintain the symmetrical (in-phase) coordination pattern is displayed (i.e., system hysteresis).

Furthermore, the collective variable relative phase (F) was found to display spatiotemporal symmetry. In simplest terms, *symmetry* is defined as a transformation that leaves the system the same afterward as it was before (Kelso, 1995, p. 54). Spatial symmetry is maintained since behaviour of the system does not depend on how the left and right hand are labelled (Jeka & Kelso, 1989). For example, the phase relation of two limbs (e.g., fingers) remains the same regardless of which limb leads or lags the other. Temporal symmetry is similarly preserved within the system because the motions of the limbs are periodic. That is, regardless of whether time is shifted one period forward, or one period backward, the phase relation remains the same and the limbs repeat at regular intervals in time (Kelso, 1995).

To theoretically explain these empirical observations, Kelso united with the physicist Herman Haken to formulate a mathematical model, referred to as the Haken-Kelso-Bunz (HKB) model, based on the concepts of synergetic theory and the tools of nonlinear dynamics.

The HKB Theoretical Model (1985) of Bimanual Coordination. Based on the aforementioned postulates (i.e., spatiotemporal symmetry, bistability, and bifurcation), Haken, Kelso, and Bunz modelled the dynamics of relative phase, F , by using a potential function, V . This potential function describes the attractor landscape and how the landscape is modified as the control parameter changes (Wallace, 1996).

Essentially, V is space symmetric. This observation can be demonstrated by the equation:

$$V(F) = V(-F) \quad (1)$$

V is also time symmetric, therefore it can be written:

$$V(F + 2\pi) = V(F) \quad (2)$$

To capture both point attractors (i.e., the observed stationary states of F at 0° and $\pm 180^\circ$), the potential function V was specified by a superposition of two cosine functions:

$$V(F) = -a \cos(F) - b \cos(2F) \quad (3)$$

where a and b are constants. If b is set to equal zero, a monostable system is demonstrated. That is, a single basin of attraction (or well) is generated between $-\pi$ (-180°) and $+\pi$ ($+180^\circ$) at 0° relative phase. The potential V for $b=0$ illustrates the in-phase (0°) pattern of coordination (see panel A, Figure A4). In contrast, if a is set to equal zero, the potential V exhibits a bistable system whereby two equivalent basins of attraction are generated. The first is located at $F=0^\circ$ whilst the second is situated at $F=\pm \pi$, which represents the coordination patterns of in- and anti-phase, respectively (see panel B, Figure A4).

In this model, the ratio b/a represents cycling frequency (i.e., the control parameter). The ratio b/a is inversely related to cycling frequency whereby high values of b/a (e.g., 1) correspond to slow cycling frequency and low values of b/a (e.g., 0) correspond to high cycling frequencies. To illustrate how the attractor layout may be modified, Haken and colleagues inserted various values for a and b in an attempt to simulate alteration in the control parameter (cycling frequency). Starting with a b/a ratio of 1 (the slowest cycling frequency), the potential function V was altered by systematically reducing the b/a ratio to 0 (the highest cycling frequency). Figure A5 illustrates the series of potential fields that are generated by changing the ratio b/a and how the attractor layout is modified as a result of such alteration. The first panel, in the upper left hand corner displays the potential function when the ratio b/a equals 1; whereas the last panel in the bottom right hand corner represents the potential function when the ratio b/a equals 0. The black ball represents the current status of the system.

In panel one ($b/a = 1$), two basins of attraction (or wells) are displayed within the dynamical layout (i.e., $\pm 180^\circ$ and 0° RP), the deeper and steeper of which occurs at 0° RP. As cycling frequency is increased (equivalent to reducing the ratio b/a), the 180° well becomes progressively shallower (de-stabilizes), until it loses its anti-

Figure A4. In A, the potential V for $b = 0$, demonstrating a monostable system with a single basin of attraction generated between -180° and $+180^\circ$ at 0° relative phase. In B, the potential V for $a = 0$, illustrating a bistable system where two basins of attraction are generated at $\pm 180^\circ$ and 0° relative phase (adapted from Haken et al., 1985).

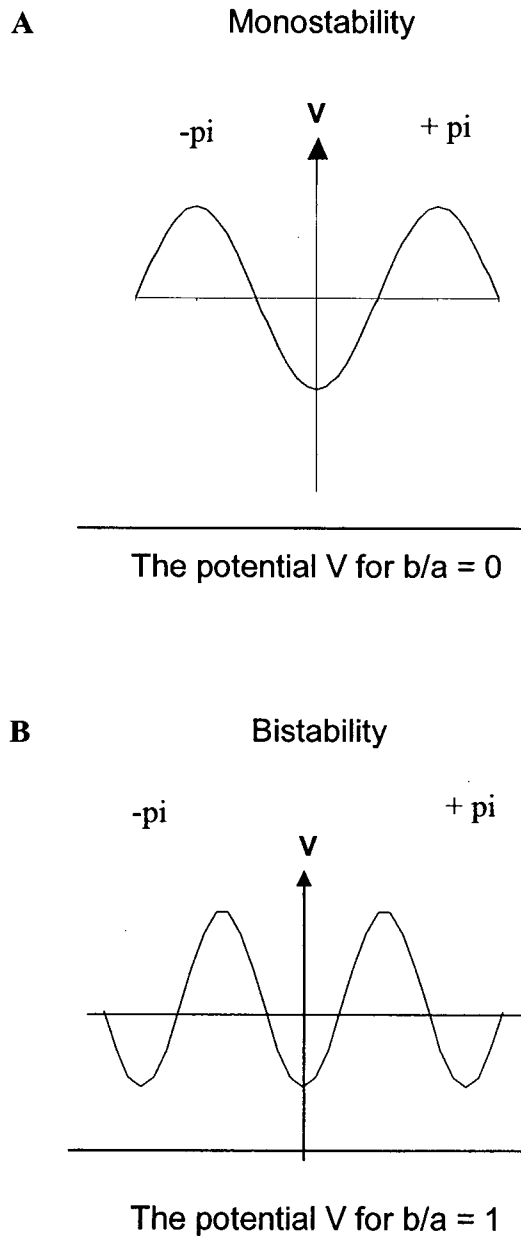
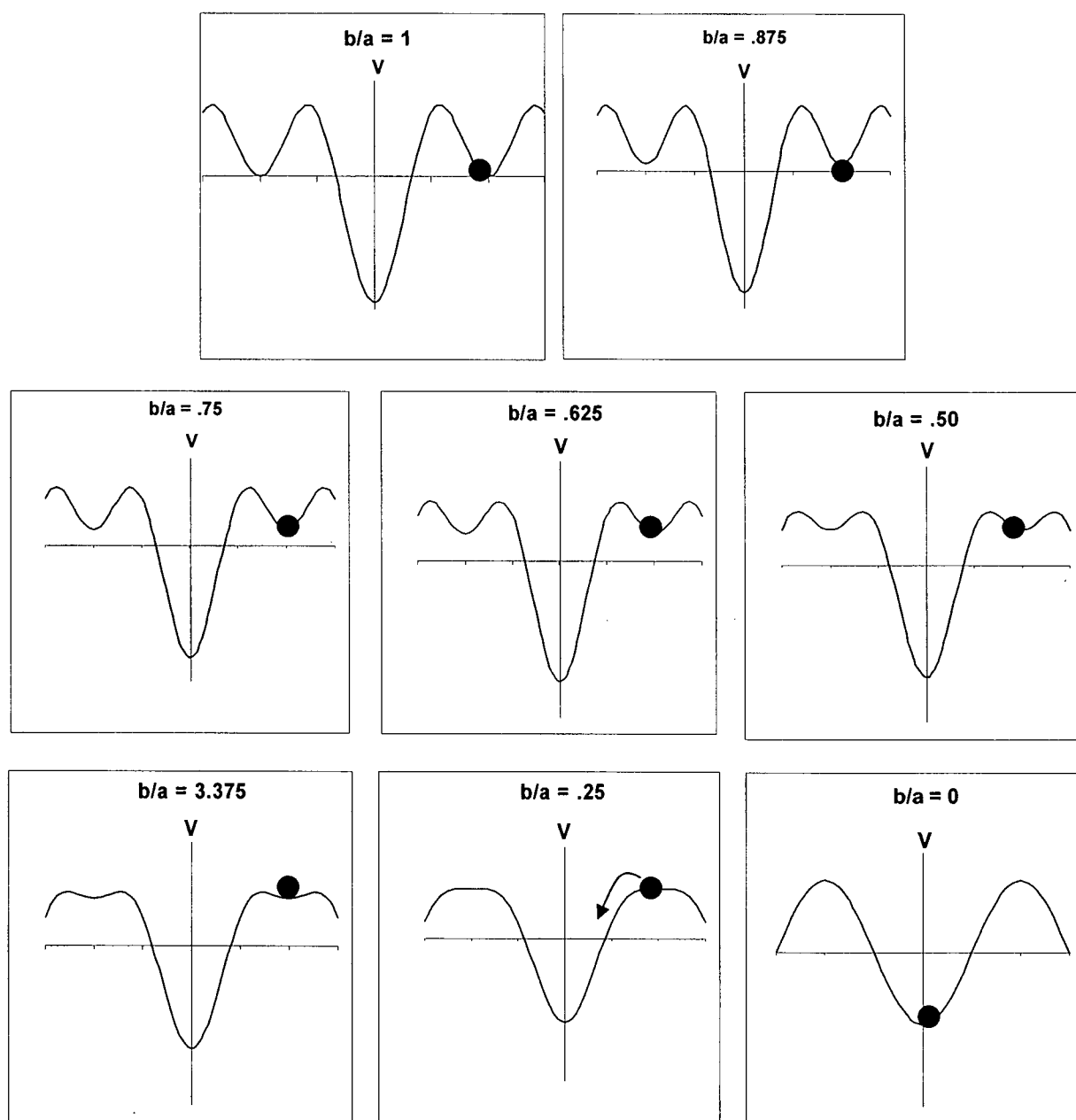


Figure A5. A series of potential fields generated by changing the ratio b/a , which represents the control parameter of cycling frequency. The upper left panel signifies the potential at the slowest cycling frequency, while the lower right panel corresponds to the potential at the fastest cycling frequency. As cycling frequency increases, the basin of attraction at 180° begins to destabilize until a critical frequency is reached, and the black ball falls into the basin of attraction at 0° (i.e., a phase transition occurs from the potential well at 180° to the more stable potential well at 0°) (adapted from Haken et al., 1985).



phase basin of attraction at high cycling frequency (i.e., $b/a = .25$). Although the potential of the well representing 0° becomes shallower, the change in b/a has less of an effect on the shape of the well at 0° when compared to the 180° well. Therefore, when cycling frequency is increased a mono- or unistable system is produced whereby a single basin of attraction remains at 0° of RP.

With respect to the black ball, initial status of the system is in the potential well of the 180° anti-phase pattern (see upper left panel). When a critical cycling frequency is reached (i.e., the basin of attraction at 180° destabilizes), a phase transition occurs where the ball falls into the potential well of the 0° in-phase pattern of coordination (see lower right panels). Although it is not displayed in Figure A5, if the control parameter is once again altered (i.e., cycling frequency is reduced), the black ball will remain at the 0° potential since the well is too deep for the ball to escape. As such, subsequent changes in the control parameter will not affect the system's preference to stay at the 0° basin of attraction.

Since the well representing the $\pm 180^\circ$ coordination pattern is shallower, and more severely influenced by changes in the control parameter, anti-phase it is said to be inherently less stable than in-phase. This notion is further supported considering (a) systematic alteration of the control parameter induces a phase transition from the $\pm 180^\circ$ coordination mode to the more stable coordination mode of 0° RP; and (b) when cycling frequency is reduced, the depth and steepness of the potential well at 0° prevents the system from leaving a symmetrical in-phase mode of coordination (i.e., the nonlinear hysteresis effect is displayed) (Jeka & Kelso, 1989; Kelso, 1995; Wallace, 1996). Most simply, the control parameter (here, oscillation frequency) modifies the attractive state or 'force' exerted by intrinsically stable states on relative phase toward in-phase or anti-phase patterns of coordination.

Summary

Rather than evoking concepts involving movement representations to explain skill acquisition and performance, dynamic pattern theory views motor behaviour as a consequence of the spontaneous organization of the motor system due to preferred states or patterns of behaviour (i.e., attractors) that arise under certain

conditions. Pioneered by Kelso and colleagues, research has shown that the motor system displays two inherently stable coordination patterns (i.e., in-phase and anti-phase) that can be performed skillfully without practice. Moreover, this behaviour can be modeled to predict how the motor system changes across time when an outside force is imposed on the system. Examining motor behaviour from a dynamical systems perspective brings with it a new set of tools to analyze and explain the mechanisms serving the emergence and stability of complex coordinating patterns.

Coordination Dynamics and Attention

The cornerstone of dynamical pattern theory is the notion that behavioural patterns emerge spontaneously from the cooperation among the systems components as a result of nonspecific changes in an external control parameter (refer back to discussion of the HKB model). However, a fundamental characteristic of human behaviour includes the capability to continuously adjust coordinated behaviour to achieve goal-directed action that is self-initiated or elicited in response to environmental contingencies. Coordination patterns can be adapted in response to: demands from the perceived environment (perceived constraints), memorized demands (learned constraints), and intended demands (intended constraints), which serve as sources of behavioural change. These specific constraints can be conceptualized as *behavioural information*. Therefore, coordination dynamics is not limited to the constraints of the intrinsic dynamics, but is also influenced by behavioural information acting as additional forces on the collective variable dynamics (relative phase), which can perturb the system toward a new (required) behavioural coordination pattern. Effectiveness of the perturbation is determined by the extent to which specific behavioural parameters and intrinsic dynamics cooperate or compete. If the required coordination pattern coincides with an intrinsic coordination tendency, the error and the variability of the produced pattern will be minimal since the intrinsic dynamics and behavioural information correspond. In contrast, if there is minimal correspondence between intrinsic dynamics and behavioural information, competition occurs whereby the produced pattern deviates

from the required pattern to the closest intrinsic attractor. This conflict results in reduced, or loss of, pattern stability. In short, cooperation and competition between intrinsic dynamics and behavioral parameters determine the coordination pattern actually produced. Therefore, behavioural information is only meaningful to the extent that it actually modifies the attractor layout of the collective variable dynamics, which is determined by the strength and location of the additional force in relation to intrinsic coordination tendencies (Schöner, Zanone, & Kelso, 1992).

Intentional Modulation of Intrinsic Dynamics

Specifically, intention stipulates a stable state of the coordination dynamics that attracts the collective variable (relative phase) to the given value. A number of experiments investigating bimanual coordination have confirmed that intentional influences can change the characteristics of the underlying coordination dynamics of intrinsic patterns. For example, these experiments have demonstrated that people are capable of intentionally switching from one intrinsic coordination pattern to another (e.g., Carson, Byblow, & Goodman, 1994, Carson, Goodman, Kelso, & Elliott, 1994; Scholz & Kelso, 1990). In this manner, intention not only permits the selection of an available intrinsic pattern, but also changes the characteristics of the coordination dynamics by destabilizing and stabilizing the initial and new (intended) patterns, respectively (see Scholz & Kelso, 1990). Lee, Blandin, and Proteau (1996) have also presented evidence, which suggests that intention can delay or inhibit spontaneous phase transitions from one pattern to another. They elicited such findings by manipulating the form of task instructions participants received while rotating their forearms in either an in-phase or anti-phase coordination state. At higher movement frequencies, one group of participants were explicitly instructed not to intervene (or to resist) the feeling to slip from anti-phase to in-phase coordination. In contrast, instruction to the second group of participants was to resist the tendency to switch coordination patterns. Although participants in the latter group exhibited decreased pattern stability and slightly slower movement frequency, they were able to override intrinsic coordination tendencies to maintain a level of performance around the anti-phase pattern. These data demonstrate that intention

has a role in determining behaviour by modifying the attractor layout of the collective variable dynamics. As a result, Schöner et al. (1992) have provided an extension of the HKB Model of bimanual coordination, which incorporates this cognitive variable into the equation. Further empirical investigation has recently focused on examining whether effects analogous to intentional influences manifest using attention as a mediating variable in the dynamics of bimanual coordination.

Effects of Attention on Coordinated Behaviour

Attention is postulated to be an important intervening factor in the voluntary stabilization of behavioural patterns given contemporary interpretations of the potential function of the coordination dynamics of a system. That is, the current perspective is to view the potential function as an 'energy expense' necessary to maintain coordination of a specific bimanual pattern at a given frequency. Most importantly, the energy involved in stabilizing the system (as determined by fluctuations of relative phase) may be viewed in terms of mechanic and metabolic energy, as well as some kind of 'mental energy' or 'effort' involving the central nervous system (CNS). In this manner, interpretation of the coordination dynamics of a system requires understanding the contributions of the CNS in stabilizing bimanual coordination patterns.

Theoretically, the potential landscape of the coordination dynamics provides an indication of the 'effort' or 'energy level' devoted by the CNS to perform a preferred coordination pattern (Temprado, Zanone, Monno, & Laurent, 1999); while the terms attention, effort, and resources are often used interchangeably, whereby attentional control implies allocation of "energetic resources" (e.g., Wickens, 1984) or "effort" (Kahneman, 1973) to the required task. In accordance with these underpinnings, reasoning suggests that the smaller the amount of energy required by the system to maintain a coordination pattern, the larger the amount of energy resources available to the CNS to further stabilize the current coordination pattern or to intentionally stabilize another pattern (Temprado et al., 1999). Allocating supplemental "energy resources" (via attention) provides an approximate index of the coordinative activity (or energy expenditure) of the CNS to maintain and perform a coordination pattern

against perturbing forces. This effort or energy is often referred to as *attentional load*.

Operationally, attentional load of preferred coordination patterns has been assessed using a dual-task paradigm. At a behavioural level, stability of a preferred coordination pattern (the primary task) is quantified by the collective variable relative phase; whereas, a discrete RT task is used to assess the costs associated with attentional load at the central level. Specifically, allocation of attentional resources are manipulated by assigning differential priority to the given tasks. While performing the required coordination pattern, participants are instructed to either: (1) share their attention between the primary and secondary task (i.e., do your 'best' in each task), or (2) maximize the stability of the performed pattern by giving priority to the coordination task (i.e., maintain an optimal level of performance on the secondary task while trying to get 'maximum' performance on the primary task). In the latter instruction condition, the amount of attentional resources allocated to the primary task increases, which serves to maintain or increase stability of the pattern.

Supplemental allocation to the primary task depletes available resources to the secondary task. Therefore, primary task performance is postulated to improve at a performance cost to the secondary task. Reaction time measures then are used as an index of the amount of intentional stabilization that is exerted on the underlying coordination dynamics.

Using this approach, Temprado et al. (1999) required participants to simultaneously perform a bimanual coordination task (i.e., in-phase or anti-phase) and a discrete RT task with different attentional priority requirements. Participants were instructed to share priority between both tasks, give priority to the bimanual task, or give priority to the RT task. Findings revealed that when attention was focused on the primary task, pattern variability decreased while response to the auditory probe increased. Reaction time also increased in the shared-attention condition (compared to giving attention priority to RT), but not to the same extent as giving priority to the bimanual task. Irrespective of whether the individual was executing in-phase or anti-phase, intentionally stabilizing a coordination pattern improved performance incurring a cost at the central level.

In all dual-task conditions, RT during the performance of in-phase was faster than RT during the simultaneous performance of anti-phase. When comparing RT to relative phase variability, findings suggest that in-phase coordination was not only the more stable of the two patterns (as indicated by lower SD or RP), but it was also the least costly to stabilize for the central nervous system (as indicated by faster RT). Similar findings have also been reported by Zanone, Temprado, & Monno (1999) and Zanone, Monno, Temprado, & Laurent (2001), who examined the performance trade-off between preferred coordination patterns and RT when manipulating the frequency of oscillation under different attentional priorities. Regardless of attentional focus, results showed that manipulating oscillation frequency away from a participant's spontaneous frequency incurs a cost at the central level for both the in-phase and anti-phase patterns of coordination (i.e., increasing frequency of oscillation destabilizes the coordination pattern, as indicated by increased variability of relative phase). However, when comparing in-phase to anti-phase patterns, a greater performance trade-off (between the coordination pattern and RT task) was reported for anti-phase. Like the findings of Temprado et al. (1999), this data also indicates that the cost of maximizing the stability of a performed pattern is larger for the anti-phase pattern than the coordinative activity of the CNS involved in performing the in-phase pattern. A tentative origin for the high cost incurred in maintaining the anti-phase pattern can be explained by the recent work of Mayville, Bressler, Fuchs, & Kelso (1999) who examined activation of primary sensorimotor areas while executing in-phase and anti-phase coordination. Results showed that execution of both patterns involves activation of parietal and frontal cortical areas. However, to sustain performance of anti-phase coordination, greater activation of the sensorimotor areas occurs.

In each of the aforementioned findings, it was found that attending to the bimanual task resulted in a smaller decrease in variability for the in-phase pattern than for the anti-phase pattern, although the change in RT was equivalent in both patterns. Since the in-phase pattern was more stable to start with, these findings suggest a floor effect whereby a minimal level of variability exists. This variability cannot be suppressed and susceptibility to further stabilization is hampered.

Temprado et al. (1999) suggest that the persistence of this phenomena originates in neurobiomechanical interactions between the subsystems that cannot be reduced by intentional modulation of the intrinsic dynamics.

Taken together, these experiments demonstrate a differential resistance between coordination patterns, which limits further stabilization. In addition, the attentional cost associated with intentional modulation is affected by the inherent (or baseline) stability that each pattern exhibits spontaneously (i.e., when no attention is given to the coordination task). Since inherent stability is determined by the coordination dynamics of a system, coordination dynamics itself can act as a constraint that limits the individual's intention to stabilize coordination patterns. Similar constraints have been documented in experiments investigating the time it takes to switch between patterns. For example, switching from in-phase to anti-phase takes longer than switching from anti-phase to in-phase (Scholz & Kelso, 1990).

To examine the effects of attentional focus on bimanual coordination dynamics and phase transitions between preferred coordination states, Monno, Chardenon, Temprado, Zanone, & Laurent (2000) required participants to execute an anti-phase pattern of coordination while gradually increasing frequency of oscillation (to induce phase transitions) under a non-priority condition (shared attention) and a priority condition (focused attention on coordination pattern). Findings revealed that phase transitions occurred for both priority conditions, but were delayed in the focused attention condition. This corresponded to an increase in pattern stability, which explains the delay in transition. Irrespective of frequency, specifically focusing attention on the bimanual coordination pattern increased RT. This supports the notion that pattern stability incurs a cost at the level of the CNS. Differential stability between in-phase and anti-phase was also demonstrated in Monno et al.'s (2000) findings. Regardless of priority condition, RT decreased after transition to the in-phase pattern.

When comparing the results of trials where a phase transition occurred to trials where a phase transition did not occur, Monno et al. (2000) found that there was no difference in the variability of RP for either priority condition. Therefore,

occurrence of a phase transition could not be predicted by the variability of relative phase. However, when comparing RT in the priority condition, the data revealed longer RT for trials that incurred a phase transition for in-phase. According to Monno et al. (2000), these findings may indicate the influence of two different mechanisms for inducing phase transitions. Transitions in the shared attention condition may result as a loss of stability of the anti-phase pattern; while transition in the focused attention condition may result from too high of an attentional load needed to sustain the pattern. As such, it was predicted that central cost associated with attentional focus may act as a control parameter triggering phase transitions in bimanual coordination.

Summary

Coordination dynamics is not limited to the constraints of the intrinsic dynamics of the system, but is also influenced by intentional modulation at the behavioural level. One intervening variable in the voluntary stabilization of behavioural patterns is attention. To study the interplay of bimanual coordination and attentional load, a traditional dual-task paradigm has recently been blended with the conceptual and methodological tools specific to dynamical pattern theory. This approach is unique in that it establishes a link between two different conceptualisations of coordination, which have traditionally been investigated independently of each other. Current empirical findings demonstrate that pattern stability (as determined by relative phase variability) strongly covaries with attentional demands (as measured by RT). Intentionally stabilizing a preferred coordination tendency incurs a cost at the central level, which is largely dependent on the intrinsic stability of the coordination pattern.

Motor Learning and Dynamic Pattern Theory

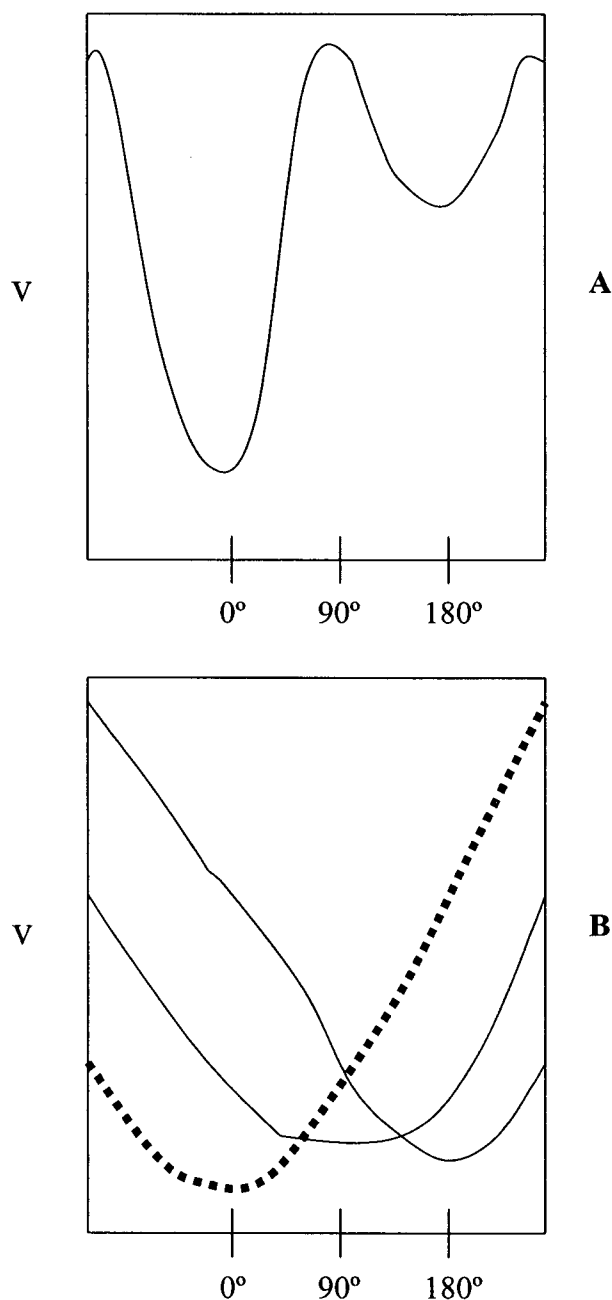
In light of the foregoing discussion, one may begin to wonder then, how dynamic pattern theory accounts for the acquisition of relative phase patterns that are not intrinsic to the human motor system. After all, in the real-world, many dual limb coordination patterns exist that demand phasing patterns other than the intrinsically stable patterns of 0° and 180° . Theoretically, the intrinsic dynamics of a system expresses the preferred or stable coordination tendencies of an individual at any one moment. In recent years, research has demonstrated that new patterns of coordination can emerge with practice as additional relatively stable attractor states (e.g., Fontaine, Lee, Swinnen, 1997; Lee, Swinnen, & Verschueren, 1995; Zanone & Kelso, 1992, 1997). This new coordination pattern is attained against the backdrop of already existing patterns. That is, when a spatiotemporal coordination pattern is acquired, the entire layout of a system's coordination dynamics is modified to incorporate the new phasing pattern into the existing landscape. As such, a to-be-learned pattern becomes part of a system's underlying dynamics through the establishment of a new attractor state within the existing pattern repertoire. Learning then, develops under the influence of pre-existing ordered patterns and involves a relatively permanent change in behaviour towards the pattern required by the environment (Wallace, 1996).

Due to the strength of pre-existing coordination tendencies, dynamical pattern theory postulates that learners may encounter considerable difficulties in establishing a new attractor state. When a required phasing pattern does not correspond to a pre-existing attractor, the intrinsic dynamics of the system and the to-be-learned task compete against one another. Early in learning, a coordination bias commonly occurs whereby the required learning pattern is drawn towards preferred or more stable attractor states (i.e., in-phase and anti-phase coordination patterns). Eventually interference from pre-existing modes of coordination is gradually overcome and the intrinsic landscape is modified to reveal a new behavioural attractor that corresponds to the required pattern. Modifications in the attractor landscape serves to reduce competition within the system. However, an important precursor or indicator of change in behaviour and phase transition to new

attractor states is variability in RP (also referred to as critical fluctuations). Early in learning, there is an initial stability in performance as the learner drifts towards preferred attractor states. As the individual attempts to break from preferred coordination tendencies, there is a decrease in the overall stability of the existing system. This is evidenced by an increase in variability of RP, which immediately precedes the individual's capability to perform the requisite phasing pattern. Therefore, critical fluctuations are indicative of the individual's search to discover the new movement. Following this, coordination variability no longer regresses, but improves with further task practice until an overall stability of the new coordination landscape is achieved (see Lee et al., 1995).

One of the most common to-be-learned patterns utilized in investigations of bimanual coordination has been the 90° relative phase pattern, involving the flexion-extension of a variety of effectors such as index fingers (e.g., Zanone & Kelso, 1992) and forearms (e.g., Lee et al., 1995). To perform 90° RP, participants must learn to coordinate the limbs with a phase offset of 90° (i.e., one limb leads the other by a quarter of a movement cycle in time). This pattern has received considerable attention since it is considered to be an unstable fixed point half-way between the attractor states of in- and anti-phase (Zanone & Kelso, 1992) (see Figure A6 – panel A). The difficulty in learning the 90° out-of-phase pattern is that individuals 'get stuck' in the early stages of learning (Lee et al., 1995) and are drawn to the more stable anti-phase pattern of coordination, or (less frequently) the in-phase pattern of coordination. Preference for these two modes may be partially explained by the fact that movements of the limbs in both in-phase and anti-phase patterns of coordination initiate and terminate in synchrony at reversal points of the movement. This suggests that the CNS naturally organizes coordination patterns by using reversal points as critical anchoring points within the movement (Delignières, Nourrit, Siourd, Leroyer, Zattara, & Micallef, 1998). Acquiring a 90° out-of-phase pattern is made difficult because the required phase lag permits only one limb to be at a reversal point at a given time. Therefore, individuals must learn how to break away from or decrease the attraction of this natural preference. With practice and effort, the attractor landscape can eventually be modified to not only include basins

Figure A6. In A, two minimal potentials are represented at 0° and 180° , which represent the intrinsic dynamics of a system prior to learning episodes. In B, the modified intrinsic landscape is displayed after learning episodes specifying the acquisition of a required relative phase of 90° . The resulting minimal potential at 90° is shifted away from the required relative phase, which indicates greater error in performance. In addition, the resulting potential well is wider signifying greater variability in performance in comparison to the potential wells at 0° and 180° (adapted from Zanone & Kelso, 1993).



of attraction at 0° and 180° , but also a stable relative phase minima at the environmentally specified phase pattern of 90° (Figure A6 – panel B).

Mapping Dynamics of Movement Patterns

With respect to learning, one of the unique features (or strengths) of the dynamical systems approach for studying bimanual coordination is that it affords the use of methods and mathematical tools from nonlinear dynamics. To examine the attractor states of the motor system for different values of relative phase at any one time, a scanning procedure is often employed. This procedure is important for assessing change in the underlying coordination dynamics as a function of learning because it permits careful documentation of behaviour before, during, and after the learning episode. Attractor states can be determined at any one time by scanning both practiced and non-practiced relative phase patterns.

The origins of the scanning procedure can be traced back to Yamanishi, Kawato, and Suzuki (1980) who required participants to make bimanual finger-tapping tasks between the hands. In the first phase of their experiment, Yamanishi et al. trained individuals to perform ten different phase relations dictated by two visual metronomes (i.e., pacing signals). Required relative phase was manipulated by varying the time delay between the onset of the two metronomes. For each relative phasing, participants were required to synchronize peak flexion of the limb with the onset of the respective metronome. Following practice, the participants attempted to reproduce all the relative phase patterns from memory, now paced only by an auditory metronome. Findings revealed that performance variability and error were lowest at 0° and 180° of relative phase. Moreover, participants had difficulty reproducing relative phase patterns that were intermediate to in-phase and anti-phase modes of coordination.

A modified version of this procedure was later adopted by Tuller and Kelso (1985). Instead of requiring participants to reproduce the patterns from memory, Tuller and Kelso manipulated the time delay between the visual metronomes to guide *unpractised* participants through a range of relative phase patterns (i.e., from 0° to 180° and back again to 360°). Findings were the same as reported by

Yamanishi et al. (1980). Again, performance variability and error were lowest at 0° , 180° , and 360° of relative phase, but increased at values intermediate to these.

Taken together, these scanning procedures provided insight into the attractor layout of the motor system. Most importantly, they provided evidence that in-phase and anti-phase are strong basins of attraction. More recently, the scanning procedure has been utilised by researchers investigating motor learning issues (e.g., Hodges & Franks, 2000, 2002; Maslovat et al., 2002; Zanone & Kelso, 1992, 1997). Rationale for using such a procedure is that scanning the attractor layout at various times throughout the entire learning period (i.e., before, during, and after acquisition) reveals the stability of each relative phase relationship at any one time. As such, the experimenter can observe any changes to the learner's landscape as he or she progresses through the learning process. In addition, it illustrates how the learning of a new pattern modifies and restructures the landscape of the intrinsic dynamics of the system, evoking change in the whole system (Kelso, 1995).

The scanning procedure is an important method for assessing the stability of various patterns of coordination. As for any experimental procedure, it is imperative that the technique provides an accurate picture of what it purports to measure. Recently, we have begun to question the use of continuous scanning procedures for mapping the dynamics of movement patterns. Rather than go into greater detail here, these concerns have been presented separately in Appendix B of this dissertation.

90° RP: The Only To-be-learned Coordination Pattern?

Research has not been limited to investigating acquisition of the 90° out-of-phase task. Rather, participants have also been required to learn other phase relations such as 45° and 135° relative phase. When performing in a phase offset of 45° , one limb leads the other by one-eighth of a complete cycle, whereas a phase offset of 135° requires that one limb leads by three-eighths of a cycle. These patterns, for example, have been used to examine the influence of intrinsic patterns on the acquisition of new coordination patterns. Based on the predictions of Zanone and Kelso (1992, 1994), Fontaine et al. (Experiment 1, 1997) examined whether

learning a 45° RP pattern is a more difficult pattern to acquire in comparison to a phase offset of 135°. The 45° RP pattern is 45° away from the in-phase pattern, whereas a 135° RP pattern is 45° away from the anti-phase pattern. Given that in-phase coordination is found to be more stable than anti-phase coordination, Zanone and Kelso predicted that an individual should experience greater difficulty inhibiting or overcoming the influence of in-phase, in comparison to the less stable pattern of anti-phase. Thus, the 135° RP pattern should be easier to learn because the anti-phase attractor should provide less competition than what would exist between the 45° RP pattern and the in-phase attractor. In essence, the stronger the attractor, the greater the competition (Schöner et al., 1992). However, Fontaine et al.'s findings did not support this prediction. Instead, they found that both patterns were difficult to acquire and in fact, the 45° RP pattern was performed with greater accuracy when compared to the 135° RP pattern. The differential stability observed between intrinsic patterns of coordination does not appear to influence the acquisition of new patterns in a specific way.

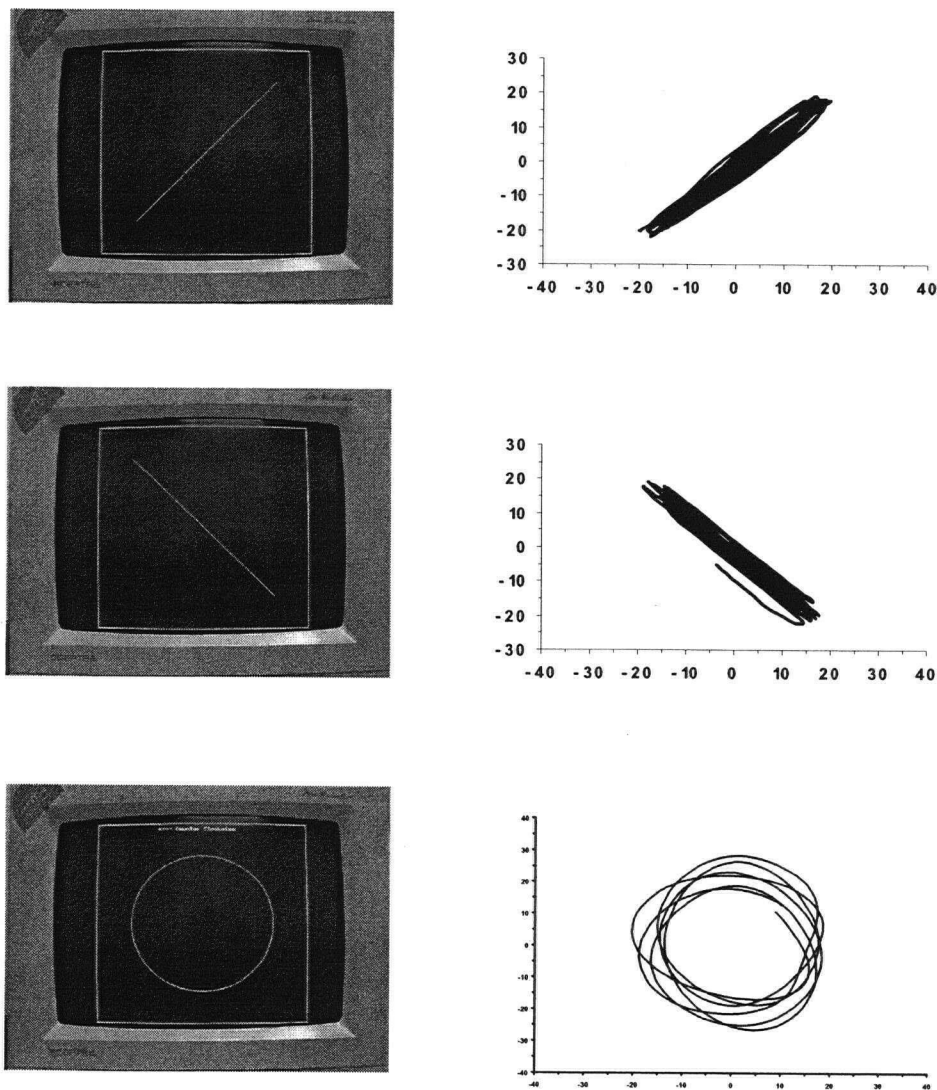
In a different manner, research has shown that practice on a 90° RP task not only increases the stability of that pattern, but also the stability of an unpractised symmetrically opposite pattern (i.e., 270° RP) (Zanone & Kelso, 1997). This effect, referred to as transfer of learning, is thought to occur in an attempt to preserve symmetry of the coordination dynamics. Prior to practice, studies in interlimb coordination have shown that the majority of individuals demonstrate bistability (i.e., the inherent coordination patterns of in- and anti-phase). The acquisition of a new phasing pattern changes the dynamic stability of bimanual coordination from a bi-stable regime to a tri-stable regime. However, this change corresponds to a reduction in symmetry. Therefore, it is postulated that increases in stability of the symmetrically opposite pattern produces a fourth stable state. The purpose of which is to restore symmetry to the coordination dynamics. Most importantly, examining stability of the 270° RP pattern, has shown that practise on a to-be-learned coordination pattern can evoke changes in the dynamic stability of an unpractised pattern.

Optimizing the Learning Process

Given the disrupting influence of preferred coordination tendencies on the learning of new coordination patterns, researchers in motor learning have recently focused their attention on identifying variables that facilitate the learning process. More specifically, they have begun examining how such factors as conditions of practice (e.g., contextual interference, Tsutsui et al., 1998), instructions (e.g., attentional focus, Hodges & Franks, 2000), or augmented feedback (e.g., real-time relative motion feedback, Lee et al., 1995) impacts the learning of a novel coordination pattern. Of specific interest to this dissertation is the empirical work that examines the provision of continuous on-line visual feedback for acquisition of the 90° out-of-phase pattern.

Augmented feedback can be visually presented in 2-dimensional form on a computer monitor. This is achieved by orthogonally plotting the displacement of the left limb against the displacement of the right limb. When correctly moving the limbs in a phase offset of 90°, the resulting relative motion plot (also referred to as a Lissajous figure) corresponds to a circle. In contrast, in-phase motions produce straight, diagonal lines between the lower left and upper right corners of the monitor (i.e., a positive sloping line), while anti-phase movements produce a negative sloping line. To specify the task goal during the learning process, a criterion template is displayed on the monitor, and the displacements of the right and left limbs are superimposed onto the template. Figure A7 illustrates this type of display. In the top panel, various criterion templates are presented, while typical performance on each required task is plotted in the bottom panel. Feedback in the form of a relative phase plot is typically presented to the performer as each limb moves in real-time (continuous on-line visual feedback) or replayed after the trial is complete (terminal visual feedback). Relative phase plots have been successfully used by a number of researchers to examine learning of new coordination patterns (e.g., Hodges & Lee, 1999; Maslovat, 2000; Swinnen et al., 1997; Tsutsui et al., 1998). This effectiveness may be attributed to a number of factors. First, relative phase plots are relatively simple in format. Second, they clearly specify the task goal. Finally, they provide learners with non-prescriptive feedback alerting them to the

Figure A7. Relative phase plots representing 0° (top panel), 180° (middle panel), and 90° (bottom panel) of relative phase. Typical criterion templates for each pattern are presented in the right panel, while examples of actual participant performance under conditions of continuous visual feedback are illustrated in the left panel.



properties and relationships inherent within the task. This specifies how the system can be controlled without specific instructions on how to achieve the required pattern. However, a critical issue that has recently surfaced is whether individuals become increasingly dependent on relative motion feedback to guide coordination movements as learning progresses. This concern arises from empirical evidence, which suggests that augmented feedback provides strong informational support when it is available, but degrades performance when it is removed or task conditions change (see Salmoni, Schmidt, & Walter, 1984). This negative learning effect is reported to be especially prevalent when augmented feedback is provided concurrently with practice of the movement (Schmidt & Wulf, 1997; van der Linden, Carraugh, & Greene, 1993; & Verschueren, Swinnen, Dom, & De Weerd, 1997; Winstein, Pohl, Cardinale, Green, Scholtz, & Waters, 1996). Rather than directing attention to the critical proprioceptive features of the task, the learner specifically focuses on the augmented feedback. As such, an internal representation of the movement is derived from feedback extrinsic to the system, rather than important task-intrinsic information. Moreover, performance is disrupted when concurrent feedback is unavailable because the learner is unable to effectively use other sources of information for execution of the movement task.

In contrast, Swinnen et al. (1997) have provided evidence supporting the concurrent use of augmented feedback for learning a new bimanual coordination pattern. This experiment compared the performance of three groups on the acquisition of a 90° out-of-phase task. Participants in the first group were provided with relative motion feedback (enhanced feedback group), while participants in the second group were only allowed normal vision of the limbs (normal feedback group). Participants in the third group were required to perform the task blindfolded, receiving only terminal relative motion feedback following every fifth (reduced feedback group). Terminal feedback was also provided to the enhanced feedback and normal feedback groups. Following practice, all three groups were required to perform test trials under real-time, normal vision, and blindfolded conditions. Results showed that the enhanced feedback group not only outperformed the remaining two groups in the presence of real-time relative motion, but was more successful when

required to perform under normal and reduced feedback conditions. This occurred even though the normal and reduced feedback groups were more familiar with the criterion condition. Although performance was shown to deteriorate in all groups whenever relative motion feedback was withdrawn, the superior performance of the enhanced feedback group under all test conditions suggests that concurrent augmented feedback holds benefits for learning a new coordination pattern.

Taking both perspectives into account, an obvious direction for the researcher is to “explore possibilities for exploiting the benefits of augmented information while reducing or eliminating its negative effect” (Swinnen, 1996, p. 44). This issue was further examined in Experiments 1 through 3 of the present dissertation.

Summary

The human motor system is not constrained to only two intrinsic coordination patterns. Rather, new patterns can emerge as additional attractor states with practise (e.g., 45°, 90°, and 135° RP). When environmental information imposes a required behavioural pattern, practice allows for the modification of the underlying dynamics of a system to include the new phasing pattern into the existing landscape. Observing changes that occur, or do not occur during the learning process has important implications for the instructional setting. For example, practise on a new coordination pattern has been shown to evoke changes in the dynamic stability of an unpractised pattern (i.e., transfer of learning). To measure changes in the coordination dynamics, methods and mathematical tools from nonlinear dynamics are used. One procedure is the continuous scanning run, which is used to probe the dynamical landscape at any one time. This is an important idea in that it permits the careful documentation of behaviour before, during, and after the learning episode.

SECTION FOUR

An Integrative Experimental Approach to Understanding Learning Phenomena

Viewing the human as a processor of information has generated much of what we currently know about motor skill acquisition (Temprado & Laurent, 1999; Wulf et al., 1999). However, recent introduction of the dynamical systems perspective for understanding motor behaviour has led a number of researchers to shift their way of thinking, dramatically impacting experimental work in a number of domains. For example, dynamic pattern theory has recently tackled issues relating to motor development (see Thelan & Smith, 1994), rehabilitation (see Scholz, 1990), and ergonomics (e.g., Chua & Weeks, 1996). Most importantly, the fundamental tenets underlying dynamical pattern theory permits investigation into complex, coordinative skills, which are more representative of real-world actions than reaction time tasks and simple movements prevalent in traditional experimental approaches to motor learning and control. From this perspective, motor coordination is examined in terms of rhythmical whole body movements (e.g., Vereijken, Whiting, & Beek, 1992), as well as multi-limb and multi-joint movements including: juggling (e.g., Beek & van Santvoord, 1992), locomotion (e.g., Peck & Turvey, 1997), bimanual coordination (e.g., Schöner & Kelso, 1988), as well as multi-limb coordination (e.g., Whittall & Getchell, 1995).

Although proponents of information-processing and dynamical systems differ in their positions concerning mental representations, there are some important similarities in motor learning concepts between the two approaches. In both paradigms, individuals are required to practice a to-be-learned task that they are unable to perform prior to acquisition. During the learning episode(s), the actor acquires a specific capability for producing the required task, the permanence of which is measured by retention and transfer tests post-acquisition. Implicit within both conceptual frameworks is the idea that if the individual is able to produce the requisite task at the end of acquisition, the performer is assumed to have learned the task (Wulf et al., 1999). Moreover, the constructs associated with motor learning are consistent when comparing both perspectives. As Lee (1998, p. 334) points out, learning from a traditional motor learning approach is considered:

1. a process, whereby the learner acquires a specific capability for producing skilled behaviour;
2. occurs as a result of practice;
3. cannot be observed directly, but inferred from tests of retention and transfer; and
4. involves a relatively permanent change in behaviour.

These constructs are also similarly expressed within the dynamical systems approach, whereby learning (Lee, 1998, p. 334):

1. occurs as a long-term transition from one set of coordination capabilities to a new set;
2. emerges because of physical interactions between controllable degrees of freedom or the environment;
3. is not observed directly but inferred from tests that include retention and transfer; and
4. involves permanence, as the relative strength of a new coordination capability is considered in terms of its capability to remain stable and attract other [less stable] coordination patterns [to it].

With respect to dynamical systems specifically, a theoretical strength is that it acknowledges the importance of pre-existing knowledge or preferred tendencies of the performer prior to learning a new movement. In traditional learning studies, learning has been indirectly inferred through the use of such performance measures as response outcome (e.g., reaction time, error scores) and response production (e.g., kinematics, electromyography). Once performance measures are acquired, a general methodological practise is to group the data and plot the averaged performance as a function of practise. In this type of approach, individual differences are seen as problematic and the learner is treated as a mere statistic (Kelso, 1995). Therefore, little can be said as to the influence of individual differences (i.e., the personal history or experiences that the learner bring to the learning environment) on the acquisition of a new form of skilled behaviour (e.g., Zanone & Kelso, 1992). In contrast to traditional approaches, methodological procedures like scanning, provide a way of quantifying the learning process, as well as describe what the individual brings with him or herself to the learning environment. By acknowledging

the importance of pre-existing knowledge, the dynamical systems perspective views the learner as the 'significant unit of analysis' (Kelso, 1996, p.61), embracing study of the individual.

Although the dynamical systems perspective provides many unique features, it is not without limitations. More specifically, a number of empirical findings exist within the literature that is difficult to account for without specifying a role for movement representations and cognition (see Wulf et al., 1999 for a review). For example, it has been well documented that both mental practice (or imagery) and observational learning, two forms of non-movement practice, have an incremental effect on learning (e.g., McCullagh, 1993; Suinn, 1993). That is, both mental practice and observational learning are more effective for the acquisition and performance of a task than no practice at all (e.g., Blandin, Proteau, & Alain, 1994). Moreover, a combination of physical practice and either form of non-movement practice may be even more effective than physical practice alone (e.g., Kohl, Ellis, & Roenker, 1992; Shea, Wulf, & Whitacre, 1999). Subsequently, the idea of cognitive representations are typically evoked to explain such findings. With respect to mental practice, a common postulation suggests that the same mental representation is activated when imaging the movement, as the performer uses to control the execution of the overt response, even though the appropriate commands are not being sent to the respective effectors. Within the context of observational learning, it has been suggested that observing performance of the required task, allows the learner to develop a cognitive representation prior to engaging in physical practice attempts. While, another hypothesis suggests that observational practice offers the learner an opportunity to engage in cognitive processing activities that would not otherwise be permitted during physical practice attempts. For example, early in learning, performing the task itself demands a great deal of cognitive effort. Therefore, other processing activities cannot take place during the concomitant performance of the requisite task. Observation provides the learner an opportunity to engage in unique information processing activities that would not otherwise be permitted until the task has become well-learned.

Findings that elicit the above interpretations are difficult to reconcile under current dynamical theory since non-physical forms of practice appear to modify the central representations of the skill being learned. This contrasts with dynamic pattern theory, which postulates that learning depends on an interaction between the physical properties of the moving system (Lee, 1998). Therefore, actively producing the required movement is essential to learning since movement patterns emerge in response to the specific demands of the task experienced as result of the interaction between perception and action.

Although two contrasting theoretical positions exist for the study of motor learning, the constructs associated with learning are similar. Moreover, each brings with it important features. Rather than adopt one position over the other, several researchers advocate a more conservative approach, with experimental efforts incorporating features central to both perspectives in a combined tactic (e.g., Chua & Weeks, 1996). Therefore, cognitive constructs such as attention can be examined by adopting methodologies derived from studies of interlimb coordination and dynamical systems theory. This approach is clearly illustrated in the present thesis. The concepts of attention and coordination dynamics were intertwined given that we investigated changes in attention demands during the learning of a new bimanual coordination task.

APPENDIX B

Using the Scanning Procedure for Mapping Dynamical Landscapes: Methodological Implications⁷

Introduction

Strength of the dynamical systems approach for studying bimanual coordination is that it offers the use of experimental procedures, which permit the careful documentation of behaviour at any stage of the learning process. One method that has been employed by researchers to systematically examine the entire layout of the individual's coordination dynamics is the scanning or probe technique. The origin of this procedure can be traced back to two sets of experiments (see Tuller & Kelso, 1989; Yamanishi, Kawato, & Suzuki, 1980), but has been utilised extensively by Zanone and Kelso (e.g., 1992, 1997) and more recently by others in the motor learning field (e.g., Hodges & Frank, 2000, 2002; Maslovat, 2002) (see *Appendix A – Mapping Coordination Dynamics*).

In a scanning trial, the participant is asked to produce a large number of different phasing patterns guided by memory, paced by an auditory metronome (e.g., Yamanishi et al., 1980), or more commonly, directed by visual metronomes (e.g., Tuller & Kelso, 1989). In the latter approach, the required relative phase is manipulated by varying the time delay between the onset of the two visual metronomes. The individual is then required to synchronize peak flexion of each limb with the onset of the respective metronome. In a quasi-continuous scanning procedure, for example, the visual stimulus gradually changes in small increments such that the metronomes initially flash in synchrony requiring the participant to flex and extend each limb at the same time (in-phase), to alternating flexion and extension, as a result of a half cycle lag in the flash times of the metronomes (anti-phase). Most importantly, the participant is required to attempt a number of intermediate relative phasing patterns along the way (e.g., 0° to 180° in steps of 15°), hence the term quasi-continuous. By examining the accuracy and stability of

⁷ The final investigation discussed in this chapter was conducted with co-investigator: D. Maslovat (Supervised by: R. Chua and I.M. Franks). A similar discussion is presented in Appendix C of D. Maslovat's Master of Science Thesis (2002).

each phase requirement, the experimenter can identify both preferred and less preferred patterns among the movement components of a system.

By running scans at different points in the learning process (e.g., before, during, or after) the stability of each relative phase relationship is revealed at any one time. As such, the experimenter can observe how the learning of a new pattern modifies and restructures the underlying coordination dynamics, evoking lasting changes in the whole system (Kelso, 1995). These adaptations are most commonly assessed by comparing the individual's dynamical landscape after practicing a new coordination pattern, to his or her landscape prior to practice. A benefit of this procedure is that the influence of individual differences on the acquisition of a new bimanual coordination pattern is taken into consideration. Therefore, the learner is treated as the 'significant unit of analysis' (Kelso, 1995, p. 161) rather than a mere statistic.

In Experiments 1 through 3, the landscape of each participant was scanned prior to learning and following the completion of each respective experiment. Pre-learning scans were included to identify the initial state of the learner, as well as individual capabilities offered as a result of the learner's history and/or past movement experiences. Scanning at the completion of the experiment provided an indication of how extended practice of a new pattern modified or restructured the landscape of the intrinsic dynamics of the system.

In pre-learning scans of the dynamical landscape, it was postulated that participants would display high variability in relative phase for patterns other than in-phase and anti-phase. Difficulty in producing intermediate relative phase patterns is due to the attracting influence of 0° and 180° relative phase, which pull behaviour towards the more stable states. Extended practice at the 90° out-of-phase criterion task was expected to lead to improved performance, as measured by an increase in accuracy and a decrease in pattern variability, such that an additional attractor was postulated to emerge at the required relative phase pattern on the post-learning scans. This was predicted considering the extended nature of practice on the criterion task. More simply, it was hypothesized that a participant's dynamical

landscape would undergo a qualitative change from a bi-stable to a tri- or multi-stable⁸ dynamic regime as a function of practice.

In a number of experiments investigating the coordination dynamics of learning, the scanning procedure has been used as a criterion for including (or excluding) participants for further testing. This practice has been adopted based on the recommendations of Zanone and Kelso (1997) who have shown that some individuals can produce patterns other than in- and anti-phase prior to practice (e.g., 45°, 135°, 90° RP). For these individuals, it is possible that a multi-stable dynamical landscape is reflective of previous practice exposure to tasks demanding high levels of coordination, such as the playing of musical instruments or video-games. Multi-stable landscapes become problematic when the to-be-learned coordination pattern already conforms to pre-existing tendencies. If the learning task is not novel to the participant, the coordination pattern performed at the end of practice may simply represent the processes of recognition or recall, rather than actual learning (see Zanone & Kelso, 1997, for further discussion). However, a primary objective of our experiments was to examine dual-task interference at skilled levels of performance, not the process of learning per se (i.e., does performing 90° RP still incur an attentional cost after the development of a stable attractor within the participants' dynamical landscape at the required value of relative phase?). For that reason, the scanning procedure was not used as a method to exclude participants. We wanted participants to become as highly skilled as possible; therefore, possessing an attractor at 90° RP prior to learning simply provided a greater opportunity to assess attention demands at skilled levels of performance. For these individuals, it was expected that results of the post-acquisition scan would demonstrate that an attractor at 90° RP is not only maintained, but also strengthened after 1, 000 trials of task-specific practice.

The purpose of Appendix B is to present the findings obtained from the scanning procedures employed in Experiments 1 to 3. General methodology used

⁸ Prior to practice, the majority of individuals demonstrate bi-stability. The acquisition of a new phasing pattern is said to change the dynamic stability of the coordination dynamics to a tri-stable regime. However, research has shown that practice on a new phasing pattern also increases the stability of the unpracticed symmetrically opposite pattern. This would produce a multi-stable regime (Zanone & Kelso, 1992, 1994, 1997).

across all investigations will be presented first. This will be followed by a specific description for each respective experiment and a discussion of the scanning results. Based on these findings, Appendix B will conclude with the presentation of a sixth experiment (see footnote #1), the purpose of which was to investigate the validity of the present scanning procedure for mapping dynamical landscapes.

General Scanning Methodology: Experiments 1-3

Apparatus

The scanning procedure was carried out pre- and post-acquisition in Experiments 1 through 3. The apparatus utilized was identical to the experimental set-up described previously (see Experiment 1 for a detailed description).

Presentation of Relative Phasing Patterns (Mode of Scanning)

Two boxes (3 cm x 5 cm) were displayed at eye level in the centre of a black computer screen, aligned horizontally, 5 cm apart (Figure B1). These two boxes served as a visual metronome whereby each box flashed on (green) for 200 ms and off (blank screen) for 800 ms at various phase relations. To manipulate relative phase, onset of the flash was controlled by a customized computer program, which allowed for the production of different phasing patterns. Participants were instructed to continuously flex and extend their arms between the two boundary markers such that they synchronized peak flexion of each arm with the onset of the ipsilateral flashing box. When the right box flashed on (green), the right arm of the individual was in peak flexion; when the left box flashed on (green), the left arm of the individual was in peak flexion (see Figure B2 for a schematic illustration of the onset of each flash for the bimanual coordination patterns of in- and anti-phase). This mode of scanning is herein referred to as 'flashing squares'.

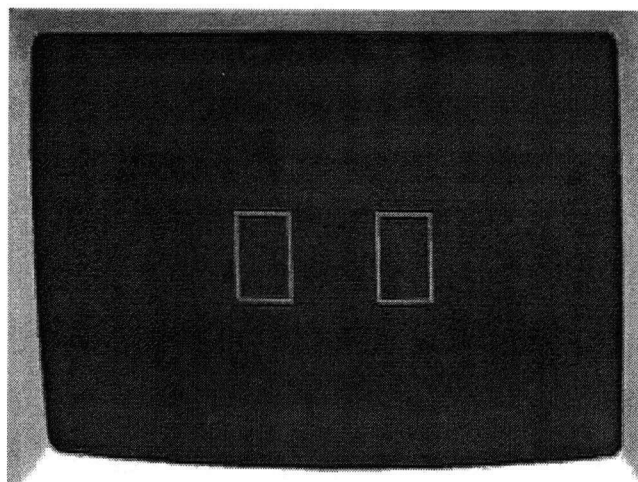


Figure B1. Two boxes, displayed in the center of the computer screen 5 cm apart, served as visual metronomes. The participants' goal was to synchronize peak flexion of each limb with the onset of the respective flashing box. This visual display represents the scanning mode referred to as 'flashing squares' (Note: neither box is flashing in the above illustration).

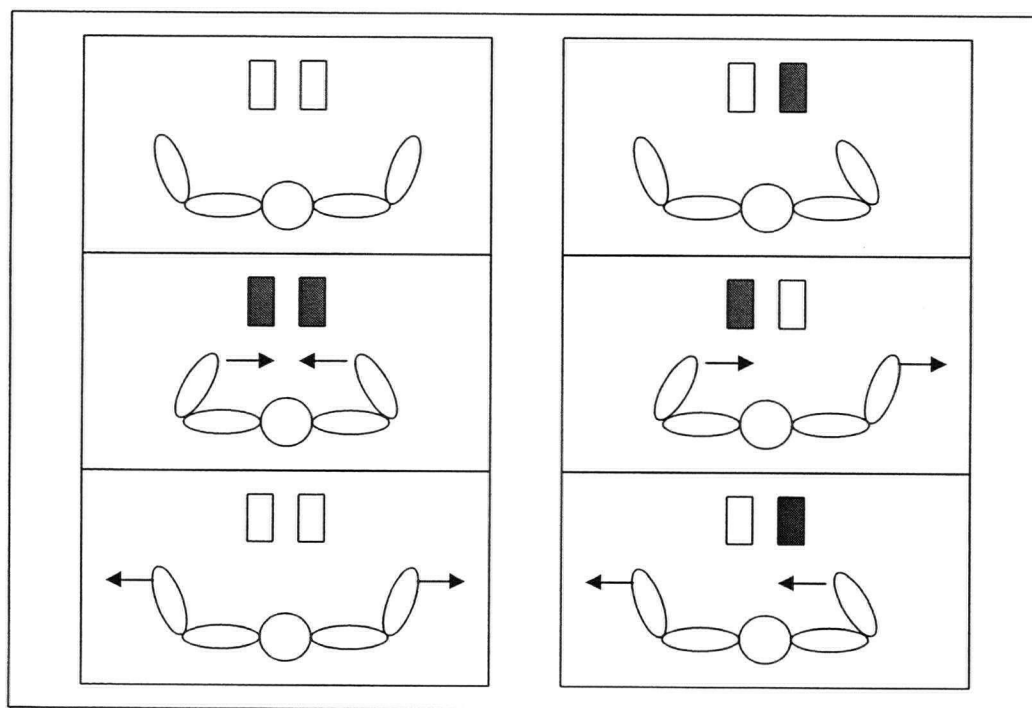


Figure B2. Illustration of the onset of each flash for the bimanual coordination patterns of in-phase (right panel) and anti-phase (left panel) for one complete movement cycle.

Experiment 1

Procedure

To map the dynamical landscape of participants prior to, and following practice, a quasi-continuous scanning procedure was adopted (see Zanone & Kelso, 1997). Continuous scanning consisted of a single trial whereby 13 relative phasing patterns were systematically increased in 15° increments, one after another, with a time delay of 15 seconds. Participants received two scanning runs pre-acquisition and two scanning runs post-acquisition. In the first run, the limbs coordinated such that the right limb led the left from a required coordination pattern of 0° (in-phase) to 180° (anti-phase) of relative phase; while the second run systematically led the limbs with a left-lead from an anti-phase (180°) pattern of coordination to an in-phase (360°) pattern of coordination. The duration of each scanning run was 3 min and 15 s, while the frequency of each cycle was held consistent at 1 Hz. To offset the potential effects of fatigue, each participant determined the time interval between scanning runs. For each scanning run, participants were instructed to keep both arms moving continuously, even if they encountered difficulty coordinating their limbs with the onset of the ipsilateral flashing square. Prior to scanning, participants familiarized themselves with the manipulanda and were provided a 12 s practice trial, whereby individuals were required to flex and extend the limbs in an in-phase pattern of coordination. Participants received up to two additional practice trials until the experimenter was satisfied that the individual understood the requirements of the task. In addition, a 'perceptual run' was provided where each participant previewed the entire scanning run before he or she physically attempted the task. During each scan run, no experimenter-given feedback was provided to the participants at any time.

Data Analyses

Discrete values of relative phase (at peak flexion) were calculated for all complete cycles of movement. Discrete values were used because it reflects the participant's ability to coordinate their limbs at a discrete point required by the task.

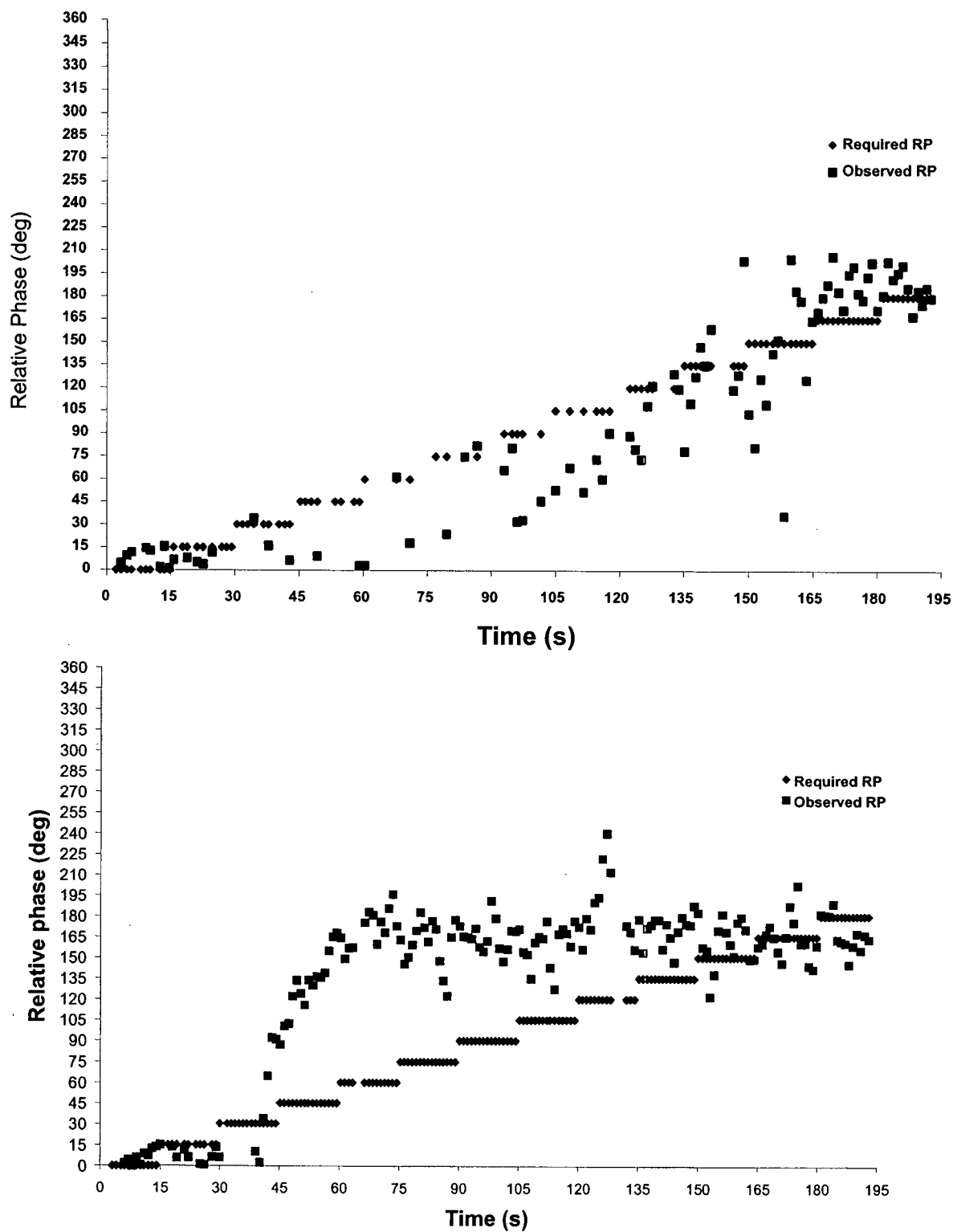
Only the last 12 s of each plateau was analyzed. No further statistical analysis was conducted on the data. The basis for this decision is outlined below.

Results and Discussion

Figure B3 (Participant 6, Experiment 1) reveals typical participant data for a pre- and post-acquisition scanning run (top and bottom panel, respectively), which probed the collective dynamics from 0° to 180° of relative phase. Visual inspection of the pre-acquisition data reveals little error for anti-phase, and even less error at the required phasing relationship of in-phase. Intermediate phasing requirements demonstrated substantial error, however, the produced patterns exhibited minimal switching behaviour towards the more intrinsically stable patterns of in-phase and anti-phase. With respect to the final probe, it was hypothesized that extended learning at 90° RP would lead to the stabilization of a new attractor state at the practiced pattern. However, the post-acquisition probe revealed a lack of qualitative change (from a bi-stable to a tri-stable regime) in the coordination dynamics. This data suggests that an attractor state did not emerge with practice at the required relative phase, even after 1, 000 acquisition trials. Instead, a very strong attraction towards anti-phase appeared to develop, when compared to the initial probe. As soon as the participant no longer required the in-phase relationship, there was a switch toward anti-phase, which remained for the duration of the probe run regardless of the task requirement.

These results are especially perplexing considering that Figure B3 represents a participant who exhibited superior performance on the 90° task in both acquisition and test trials. In acquisition, for example, the participant coordinated the limbs to produce one circle pattern on the very first trial, and a consistent 90° relative phase pattern emerged within the first 20 trials (refer back to Figure 2.5, bottom panel; also see Figure 2.8 for the time course of 90° RP performance). This participant was also able to perform 90° RP in no-feedback transfer conditions with accuracy and consistency, which is illustrated in Figure 2.13 in the form of Lissajous figures. Based on the individual's performance in both acquisition and transfer, it seems counterintuitive to postulate that a multi-stable regime in the coordination dynamics

Figure B3. Required relative phase and observed relative phase as a function of time for continuous pre-practice (top panel) and post-practice (bottom panel) scanning runs for Participant 6, Experiment 1.



would not have emerged after extended practice. Zanone and Kelso (1997) have demonstrated the emergence of an attractor state at a to-be-learned pattern after only a short amount of practice. Interesting, when inspecting the data of all our participants, none of the post-acquisition scans provided an indication that an attractor state had emerged at 90° RP following 1, 000 practice trials. We suggest two possible reasons for these findings.

A continuous scan consists of a single trial of many different phasing patterns, presented one after another without any pause in trial. Therefore, participant performance may be confounded by the ability to perceive (1) incremental changes in relative phase, or (2) a difference in relative phase patterns from anti-phase. For example, Hodges, Chua, & Franks (2002) have recently investigated the capability to detect change as it relates to the scanning task. Although participants were capable of perceiving a change from 0° to 15°, their detection accuracy dropped to 70% with a change from 15° to 30°, and continued to decline as relative phase was increased in 15° increments to 210° RP. In general, Hodges et al. (2002) found that individuals were poor at discriminating perceptual changes. This implies that performance on a continuous scanning task may be confounded by the individuals' capability to perceive changes in required relative phase.

A second limitation of employing a continuous scan procedure for mapping dynamical landscapes is the problem of carry-over effects. Recently, McGarry, Hodges, Bredin, Franks, & Chua (2000) have investigated the inherent variability of the scanning procedure in probing an individual's intrinsic dynamics by examining the reproducibility of the probe technique. In their first experiment, participants were required to complete one continuous scanning run per day for five days. Beginning at 0° RP, the phasing requirements were systematically increased in 15° increments, every 12 seconds, for a total of 24 steps. When comparing 0° RP and 360° RP, results revealed that performance of 360° RP was less accurate, as well as more variable across scans for each participant even though both patterns describe the same phase relation. Therefore, a limitation of the continuous scan is that attainment of a required relative phase may be influenced by within-in scan history.

Within the literature, it has been suggested that carry-over effects may be the reason that recent investigations have failed to support Zanone and Kelso's (1992, 1994) predictions (Fontaine et al., 1997; Lee et al., 1995; Smethurst & Carson, 2001). Using continuous scans of the coordination dynamics Zanone and Kelso showed that the accuracy and stability of the anti-phase pattern decreased when individuals learned to coordinate the limbs in a phase offset of 90° . They interpreted this result by suggesting that stabilization of a new coordination pattern caused destabilization of another (i.e., the addition and deletion of attractor states). However, by reversing the order of the phasing requirements (i.e., start at 180° RP and end at 0° RP) Fontaine et al. (1997) suggested that the opposite effect might be observed when scanning the coordination dynamics. Instead of anti-phase, the in-phase pattern might appear to destabilize. As such, the influence of carry-over effects is an important methodological concern for the researcher.

To address this limitation, a discrete method of scanning was adopted in McGarry et al.'s (2000) second experiment. In this study, participants were required to perform each phase relation one at a time in random order for 12 s. When compared to the continuous scan, findings demonstrated that discrete scan performance was not influenced in the same manner by remnants of previously performed patterns. Given our present findings, a discrete method of scanning was adopted for Experiments 2 and 3.

Experiments 2 and 3

All methods were identical to those previously described with the following exceptions.

Procedure

Participants performed 12 different patterns (13 plateaus) of relative phase one at a time, in random order, for 15 s (i.e., 1 trial of 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, 330°, and 360° of relative phase) at a frequency of 1 Hz. Participants were told that each trial would require a different phasing requirement of the limbs and some criterion patterns would be more difficult than others. Regardless of the difficulty, individuals were instructed to keep moving the limbs at the required frequency.

Prior to each test trial, participants previewed the whole trial before attempting the required phasing pattern. Participants were presented with 12 'perceptual runs', each of which immediately preceded the person's attempt at the required phase relation.

Results and Discussion

When scanning the coordination dynamics in a continuous manner, results demonstrate that the performance at any one phasing requirement may be influenced by the performance of a previously performed relative phase pattern. Therefore, a discrete method of scanning was used in Experiments 2 and 3 to limit the influence of carry-over effects (McGarry et al, 2000; Experiment 1, this dissertation). A second advantage of using a discrete scanning method is that participants are also aware that they are attempting twelve different relative phasing patterns and it is clear when an attempt at a new phasing requirement starts and ends. When changes to the required phase offset are made on-line during a continuous scanning run, participants do not necessarily perceive that a change in relative phase requirements have even occurred (Hodges et al., 2002). As such, a continuous scanning run may be more indicative of individual differences in pattern recognition than an accurate description of the coordination dynamics of the person.

In Experiments 2 and 3, we predicted that individuals would demonstrate high variability in relative phase for patterns intermediate to in-phase and anti-phase in pre-scans of the attractor layout. However, after 1, 000 practice trials of 90° RP, post-scans would reveal the emergence of an attractor state at the criterion pattern. For participants already possessing an attractor at 90° RP, we predicted that results of the post-acquisition scan would demonstrate that an attractor at 90° RP is not only maintained, but also strengthened. Unfortunately, the findings that we obtained did not necessarily support our predictions.

Figures B4, B6, B8, and B10 illustrate the range of participant data generated for pre- and post-acquisition discrete scanning runs for relative phase values from 0° to 180° RP (top and bottom panel, respectively). For each participant discussed, mean RP across acquisition is presented in Figures B5, B7, B9, and B11, respectively. For Participant 4 (Experiment 2), the scanning data reveals a preferred tendency towards 0° and 180° prior to practice. In addition, low error at the 90° RP scan ($M = 80.5^\circ$) suggests that the individual might already possess an affinity (or tri-stable regime) for phasing requirements demanding an offset of 90° (see Figure B4, top panel). Mean RP data collected during acquisition shows that the individual performed the 90° RP with consistency and accuracy during both the vision and no-vision segments throughout the 1, 000 practice trials (Figure B5). Following practice, post-scans showed an even stronger attraction to the 90° RP pattern (Figure B4, bottom panel). These data support our theoretical predictions.

Results for Participant 3, an individual who experienced great difficulty acquiring the 90° RP task in Experiment 2, can also be explained. For this individual, pre-scans revealed a strong bias to 0° RP and 180° RP. There was no evidence of a pre-existing attractor state at 90° prior to practice (Figure B6, top panel). During acquisition, performance improved practice, but the individual never exhibited accurate and consistent levels of performance at the criterion

Figure B4. Required relative phase and observed relative phase for discrete pre- and post-practice scanning runs for Participant 4 (Experiment 2) (Error bars = SD).

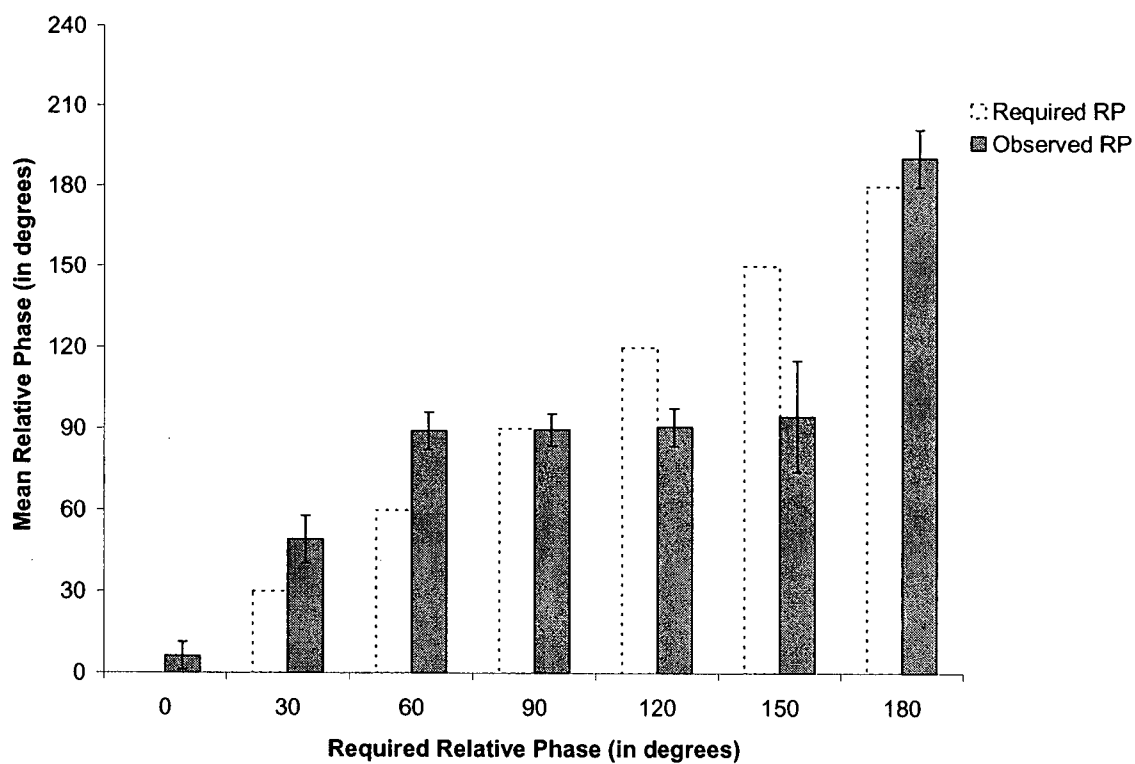
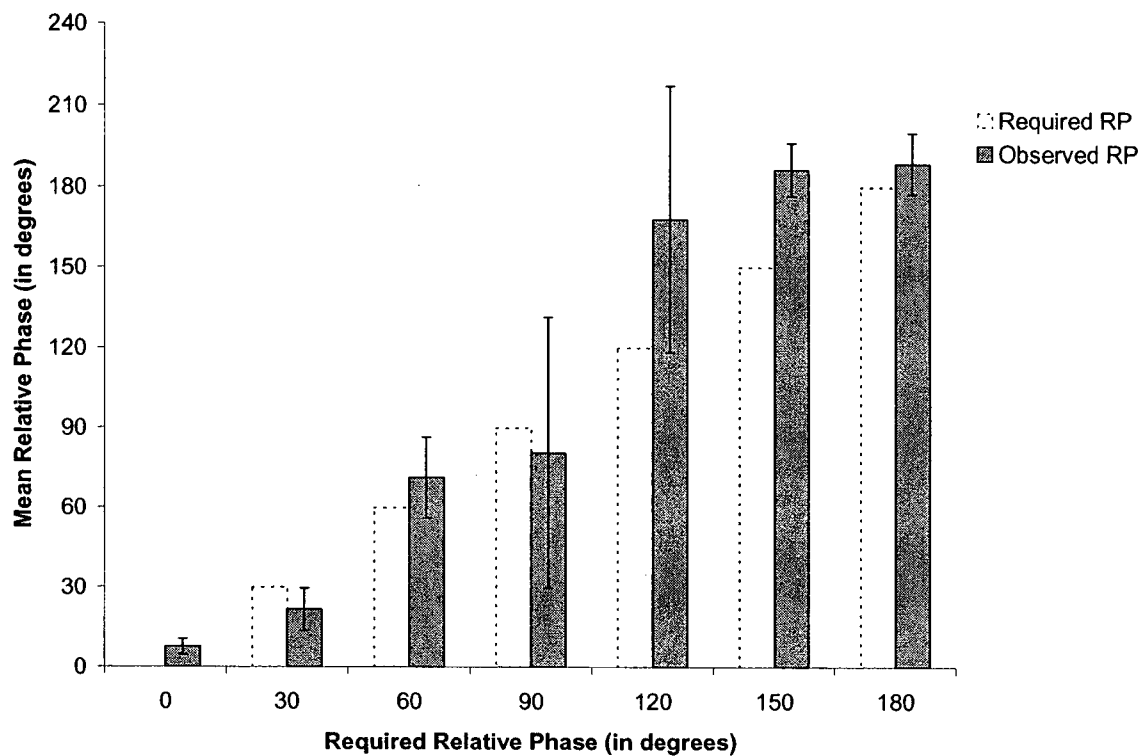


Figure B5. Mean RP for Participant 4 (Experiment 2) plotted in blocks of 20 trials across nine days of acquisition for the no-vision segment and the vision segment.

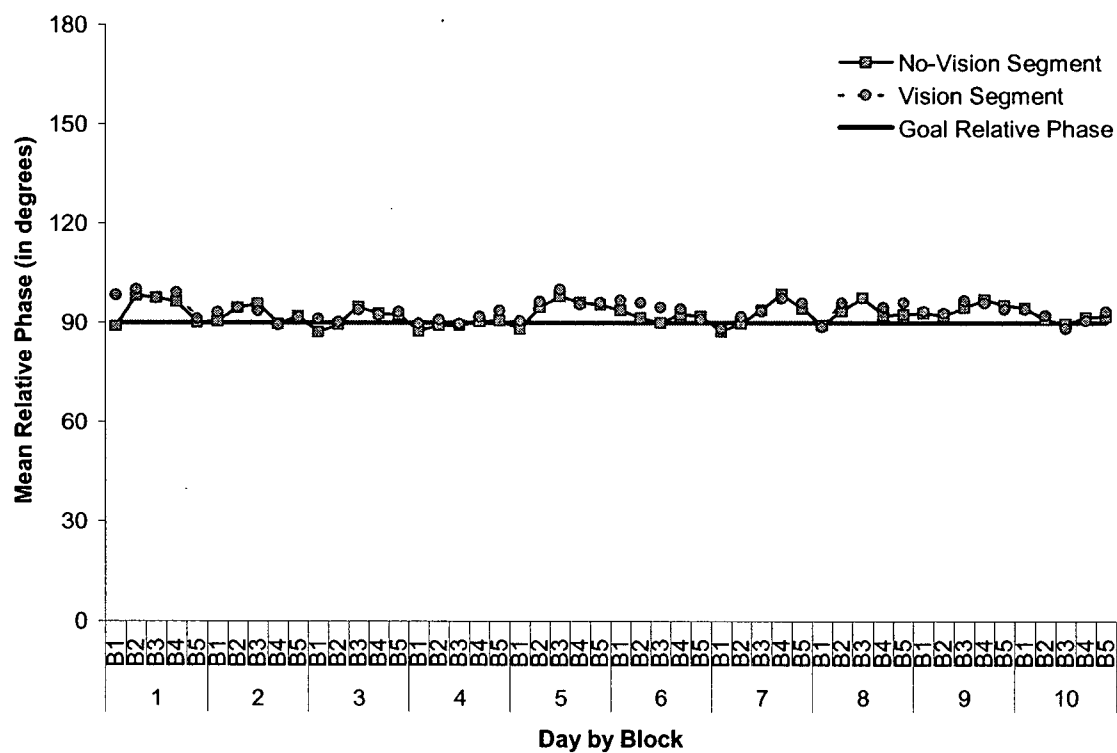


Figure B6. Required relative phase and observed relative phase for discrete pre- and post-practice scanning runs for Participant 3 (Experiment 2) (Error bars = SD).

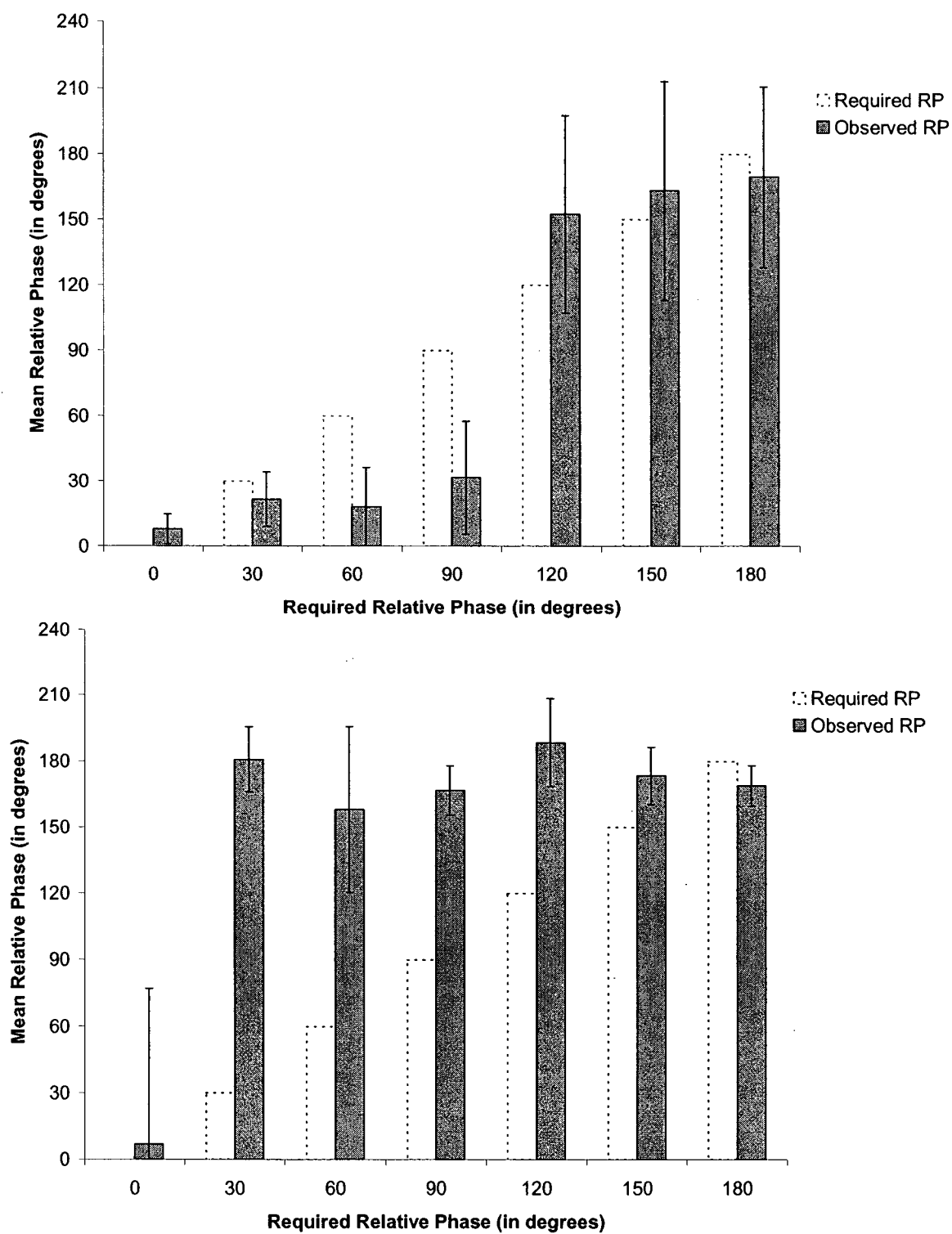
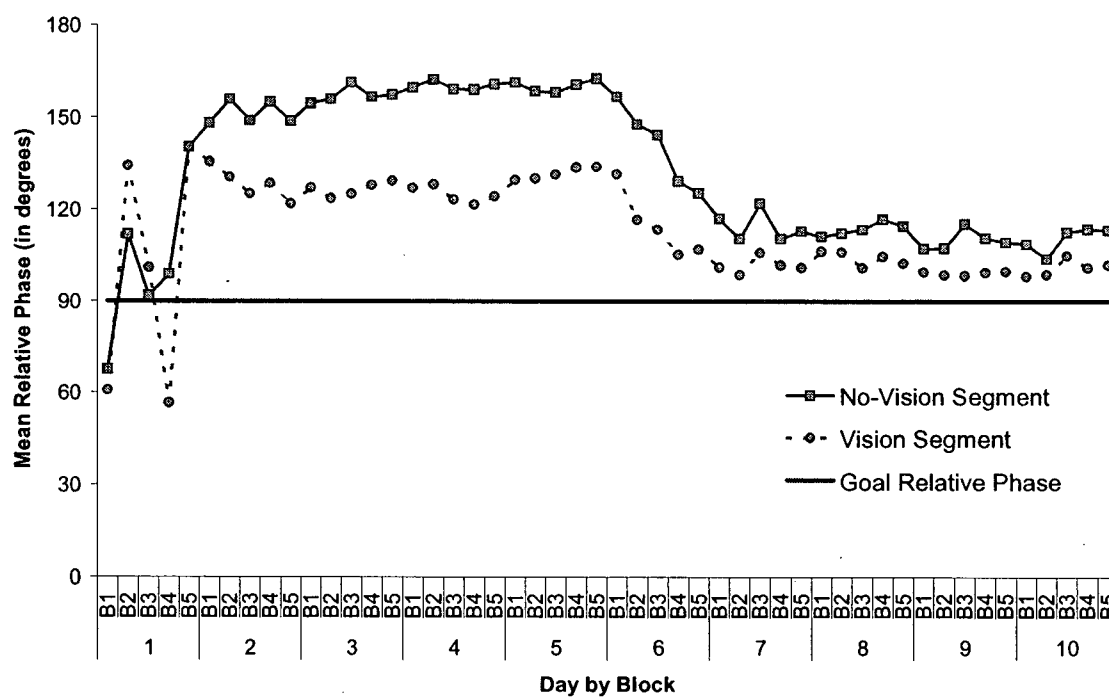


Figure B7. Mean RP for Participant 3 (Experiment 2) plotted in blocks of 20 trials across nine days of acquisition for the no-vision segment and the vision segment.



task (Figure B7). Given this, one would not postulate an emergence of an attractor at 90° . This prediction was supported because post-scans revealed no development of an attractor at the required learning pattern. Instead, there was an even stronger attraction to the anti-phase pattern. This might be explained by suggesting that following acquisition, the participant recognized when a phasing requirement did not require synchronization of the limbs. Therefore, the participant made every attempt to perform a pattern that was not in-phase. However, because an attractor was not established at 90° RP, the individual was drawn to anti-phase coordination, a preferred behavioural tendency.

In contrast, we also obtained data from several participants that were highly inconsistent with our theoretical predictions, and rather difficult to explain. In Figure B8, for example, the scanning data for Participant 1 (Experiment 3) reveals low error at 0° , 90° , and 180° of relative phase prior to practice. Accordingly, this would suggest that the individual already possesses a multi-stable movement regime. Mean RP data collected during acquisition supports this interpretation as the individual was quickly able to perform 90° RP with consistency and accuracy during both the vision and no-vision trial segments (Figure B9). In contrast to our predictions, however, post-scan data demonstrates that an attractor at 90° RP pattern no longer exists. That is, the 90° attractor actually destabilized during learning.

For Participant 2 (Experiment 3), the dynamical landscape appears to be relatively unaffected as there is no change in attractor stability from pre- to post-acquisition scanning runs. This participant exhibits a very strong attraction to anti-phase whenever a phasing pattern other than in-phase is required (Figure B10). Once again, although practice resulted in a very accurate and consistent display of 90° during acquisition (Figure B11) this was not accurately reflected in post-scans of the coordination dynamics. Table B1 displays individual data for all participants from 0° to 180° RP for discrete pre- and post-scans of the coordination dynamics for Experiments 2 and 3.

Figure B8. Required relative phase and observed relative phase for discrete pre- and post-practice scanning runs for Participant 1 (Experiment 2) (Error bars = SD).

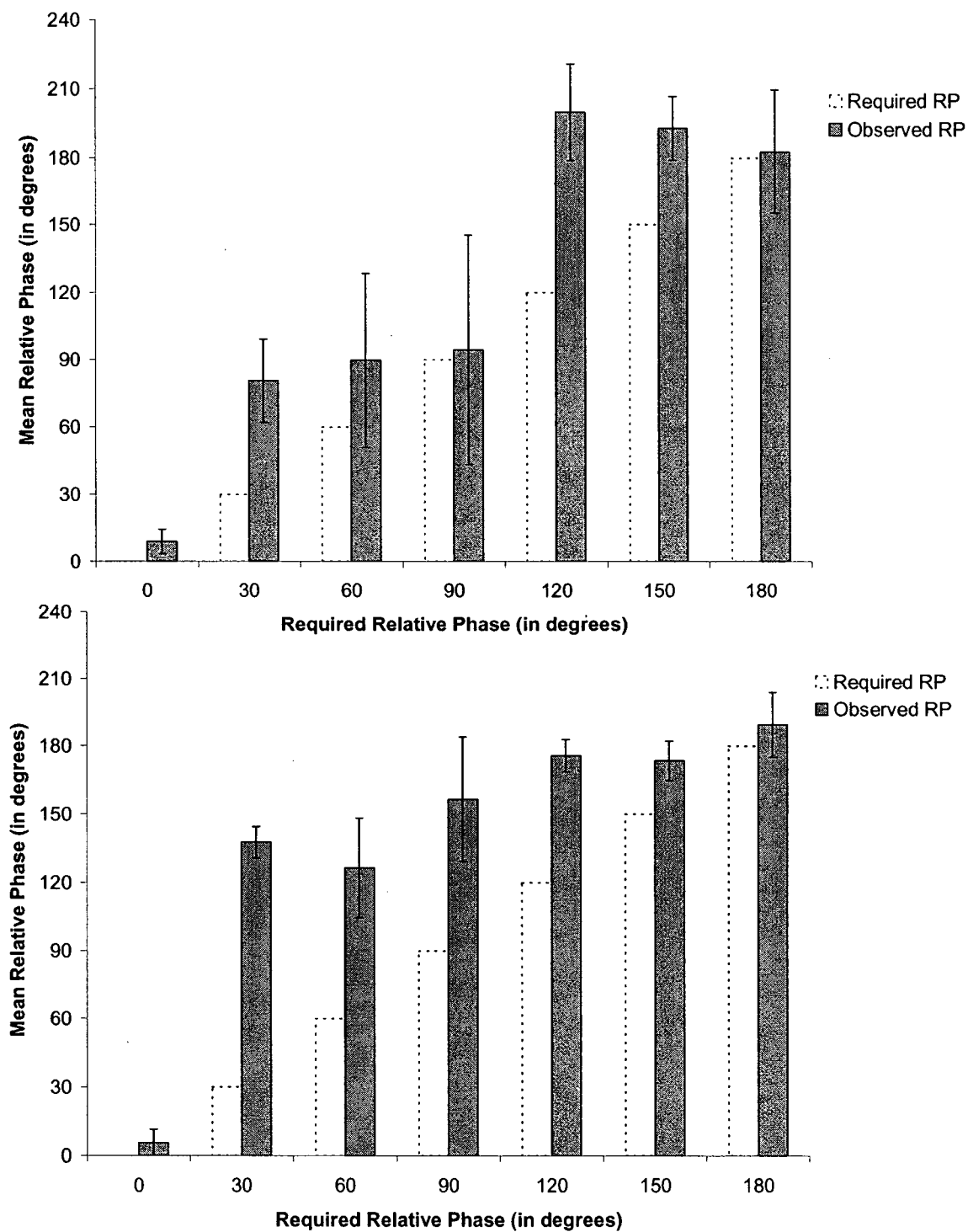


Figure B9. Mean RP for Participant 1 (Experiment 2) plotted in blocks of 20 trials across nine days of acquisition for the no-vision segment and the vision segment.

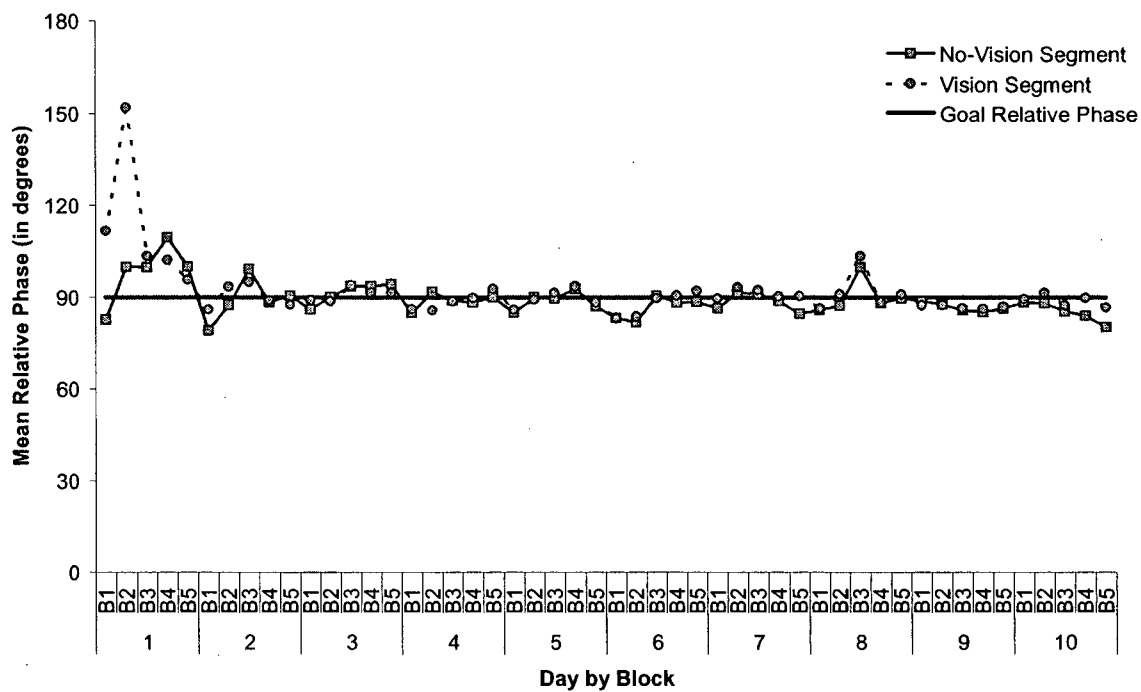


Figure B10. Required relative phase and observed relative phase for discrete pre- and post-practice scanning runs for Participant 2 (Experiment 3) (Error bars = SD).

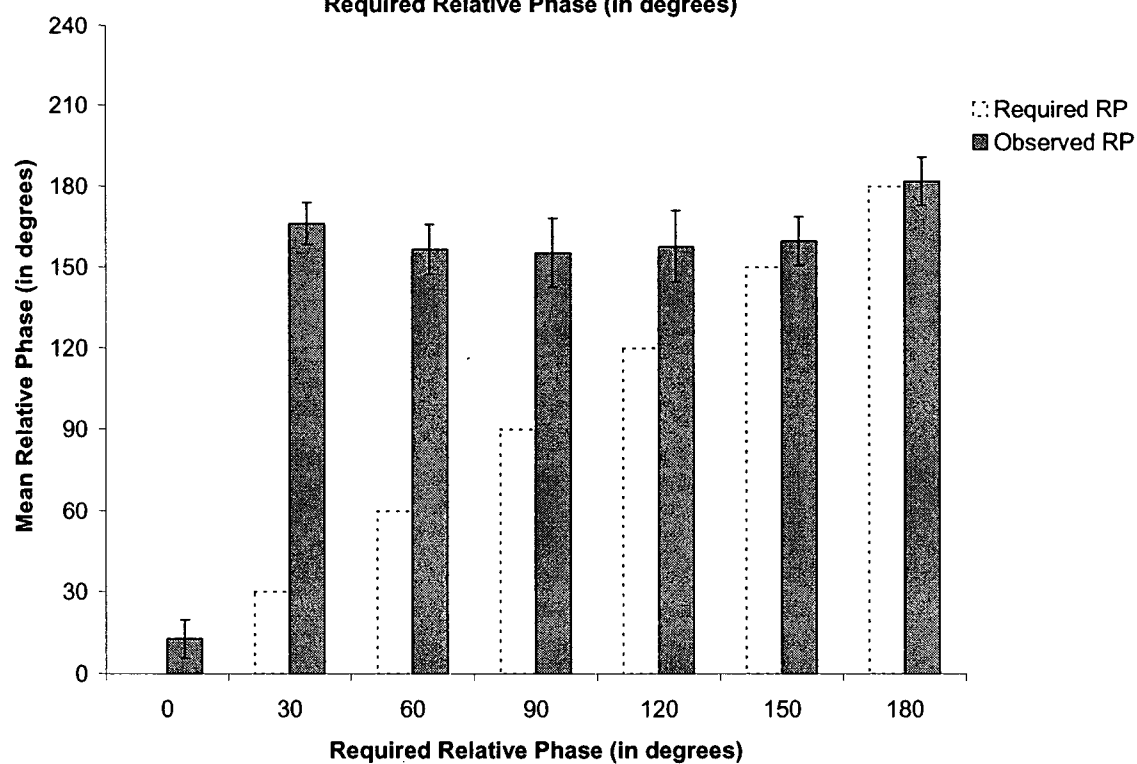
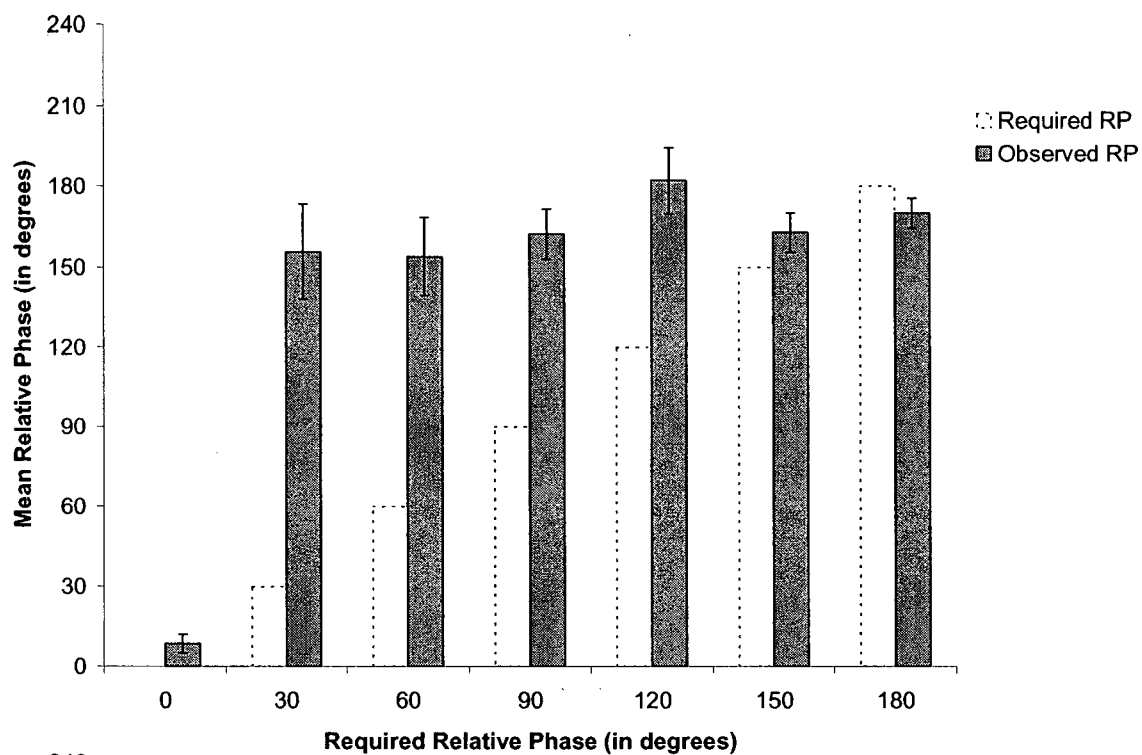


Figure B11. Mean RP for Participant 2 (Experiment 3) plotted in blocks of 20 trials across nine days of acquisition for the no-vision segment and the vision segment.

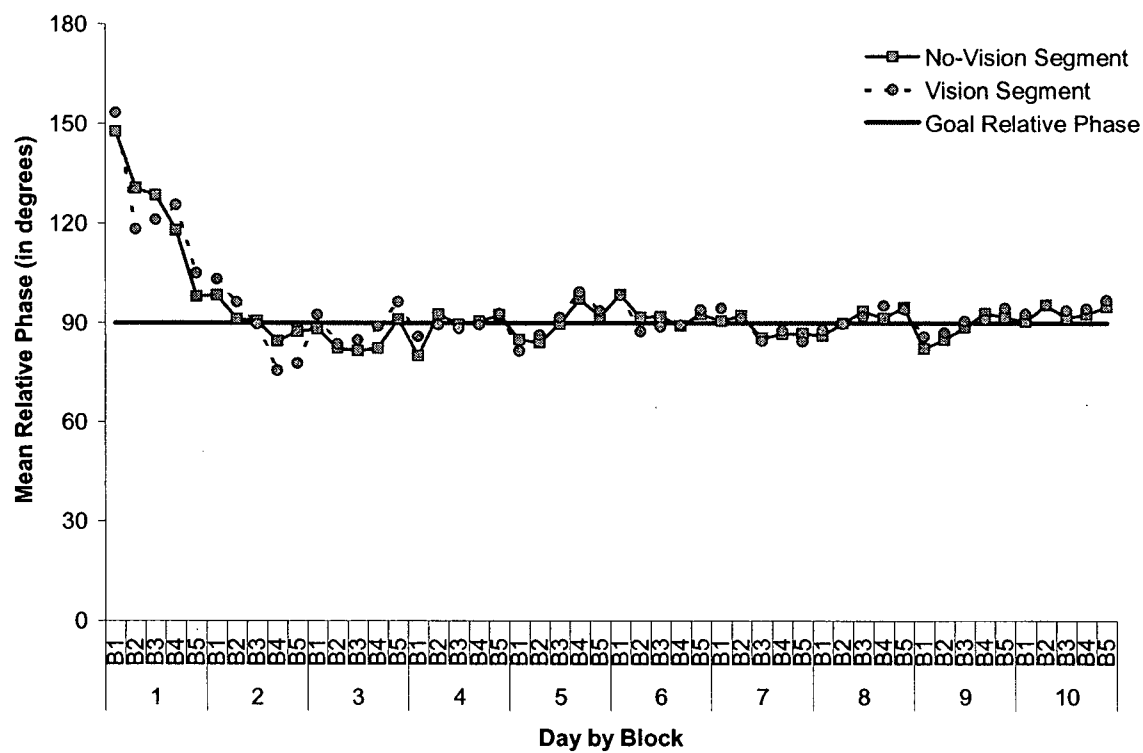


Table B1

Individual Participant Data from 0° to 180° RP for Discrete Pre- and Post-Scans of the Coordination Dynamics, Experiments 2 and 3.

		Relative Phase (RP)													
		0°		30°		60°		90°		120°		150°		180°	
Experiment	Participant	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
2	1*	8.9	5.4	80.5	137.5	89.7	126.3	94.3	156.5	199.9	175.6	192.9	173.4	182.5	189.4
2	2	8.1	3.1	54.2	53.9	50.2	53.5	172.2	94.2	197.3	166.7	187.8	181.4	191.2	182.7
2	3*	7.8	6.7	21.6	180.7	18.1	158.0	31.5	166.6	152.4	188.3	163.1	173.3	169.4	168.7
2	4*	7.6	6.2	21.4	49.1	71.3	89.0	80.5	89.5	167.8	90.6	186.4	94.5	188.6	190.4
2	5	0.9	6.1	126.4	119.0	138.5	150.4	164.6	142.3	198.3	171.2	187.0	184.5	173.3	191.5
2	6	0.1	1.1	101.8	80.7	122.4	76.4	143.4	84.6	189.9	107.6	191.6	174.8	183.5	182.2
3	1	5.2	9.5	68.7	83.7	67.6	86.0	21.9	84.3	194.3	168.8	105.6	178.0	193.3	175.4
3	2†	8.5	12.7	155.7	166.0	143.9	156.5	162.2	155.2	182.1	157.5	162.8	159.6	169.8	181.8
3	3	0.7	7.7	57.7	113.6	90.0	142.9	91.2	155.7	80.4	162.7	203.5	191.2	198.7	186.0
3	4	1.1	4.2	51.3	51.7	64.5	56.0	143.8	90.1	110.7	99.0	178.9	186.1	183.6	181.2
3	5	1.3	2.2	43.6	51.1	65.9	98.2	119.1	85.0	81.5	111.5	191.7	206.3	210.9	191.6
3	6	6.6	5.0	108.6	114.4	126.2	117.2	120.2	112.7	135.0	161.4	182.3	191.3	184.1	182.4

* Participant 1 (see Figures B8-B9); Participant 3 (see Figures B6-B7); Participant 4 (see Figures B4-B5)

† Participant 2 (see Figures B10-B11).

One reason for the inconsistent findings may lie in the different methods used to learn the new bimanual coordination pattern and to scan the coordination dynamics. The scanning procedure utilised a discrete visual metronome in the form of flashing square stimuli, while participants were provided with relative motion feedback in the form of Lissajous figures during learning. Therefore, one question that arises is whether using a visual metronome scanning procedure is valid if the method of acquisition is different. The following experiment was designed to investigate this question.

Evaluation of Scanning Methods for Mapping Dynamical Landscapes

(D. Maslovat, S.S.D. Bredin, R. Chua, and I.M. Franks)

The purpose of the scanning procedure is to observe how the learning of a new pattern modifies and restructures the underlying coordination dynamics by comparing a participant's dynamical landscape after practice, to his or her inherent coordination tendencies prior to practice. As such, it is imperative that the scanning procedure provides an accurate picture of the individual's intrinsic landscape. In the acquisition sessions of the aforementioned experiments, participants acquired 90° RP using Lissajous figures (refer back to methods Experiment 1) rather than flashing squares (see Figure B1 and B2). Therefore, one question that arises is whether using a visual metronome scanning procedure is valid if the method of acquisition is different? The present experiment was conducted to explore this methodological issue. Specifically, the purpose of this investigation was to examine and evaluate two different methods of the scanning procedure.

Participants engaged in one session of 75 practice trials. The goal of the practice session was to learn how to coordinate the limbs in a phase offset of 90°. Scans of the coordination dynamics were performed before and after the practice trials and later compared to early and late acquisition trials. Four groups of participants performed scanning and acquisition trials using a combination of either: a) an auditory metronome and continuous on-line visual feedback in the form of a

relative motion plot, or b) a discrete visual metronome in the form of two flashing square stimuli.

Method

Participants

Informed consent was received from twenty self-professed right-handed individuals from a university population ($n = 10$ females; $n = 10$ males). The mean age of participants was 24.8 years ($SD = 2.8$, range = 19-28 years). None of the participants had previous exposure to the to-be performed task, and all were naïve to the purpose of the experiment.

Participants were randomly assigned to one of four groups based on the mode of presentation during acquisition and the method of scanning ($n = 5$ per group). Half of the participants were provided with relative motion feedback to learn the 90° pattern, while the other half received flashing square stimuli. For the scanning run, half of the participants received relative motion feedback and the other half received flashing square stimuli. Using all possible combinations, the four groups were defined as: Lissajous-Square (L-S); Lissajous – Lissajous (L-L); Square-Lissajous (S-L); and Square-Square (SS). The first position in each group label refers to the mode of presentation during acquisition, while the second label position refers to the method of scanning.

The experiment was carried out according to the ethical guidelines set by the University Behavioural Science Screening Committee for research involving human participants. All participants received a remuneration of \$10 CN upon completion of the experiment.

Apparatus

The same apparatus and experimental set-up was used as previously described.

Procedure

Orientation

Participants were first given two practice trials to familiarize themselves with the movement of the apparatus. Participants were instructed that all trials lasted 15 s, and an auditory tone would signal the start and stop of each trial. Participants were told to make continuous movements of the limbs. The criterion for one full movement cycle was explained to consist of the full moving distance between the "IN" and "OUT" markers so that each hand returned to the same starting position.

Following general instructions, participants were asked to perform a series of 'natural' or 'intrinsic' patterns of coordination. More specifically, participants were asked to perform one trial of: (1) in-phase coordination, (2) anti-phase coordination, and (3) any pattern different than in-phase or anti-phase, respectively. Prior to performing in-phase and anti-phase, the participant received instructions on how to coordinate the limbs to produce the phasing requirements. For the third trial, participants were told that they could coordinate their limbs in any manner as long as they were moving in a different phase relation than in- or anti-phase, and they felt comfortable performing it for a long period of time. These trials provided a baseline measure of pre-existing coordination tendencies prior to the start of the experiment. This method also provided an opportunity to discover any other coordination preferences unique to the individual. All trials were performed in front of a blank computer screen.

Participants were then given specific orientation trials in accordance with their group assignment. Participants in the L-S and S-L groups were familiarized with relative motion feedback and flashing square stimuli. The L-L group received practice trials using concurrent on-line feedback, while the S-S group was oriented to flashing square stimuli. To avoid learning effects, all practice trials were performed using pre-existing modes of coordination. All groups performed five orientation trials to assist them with understanding the expectations of the task and conditions they would be exposed to.

Scanning Task

Participants were required to perform discrete trials of 12 different relative phase patterns (0° , 30° , 60° , 90° , 120° , 150° , 180° , 210° , 240° , 270° , 300° , and 330°) by flexing and extending the arms between the boundary markers. A complete scanning procedure consisted of an initial trial of 90° relative phase, followed by discrete trials of all 12 different relative phase patterns, randomly presented, followed by a final trial of the 90° pattern. In total, 14 trials were collected, three of which required a phase offset of 90° .

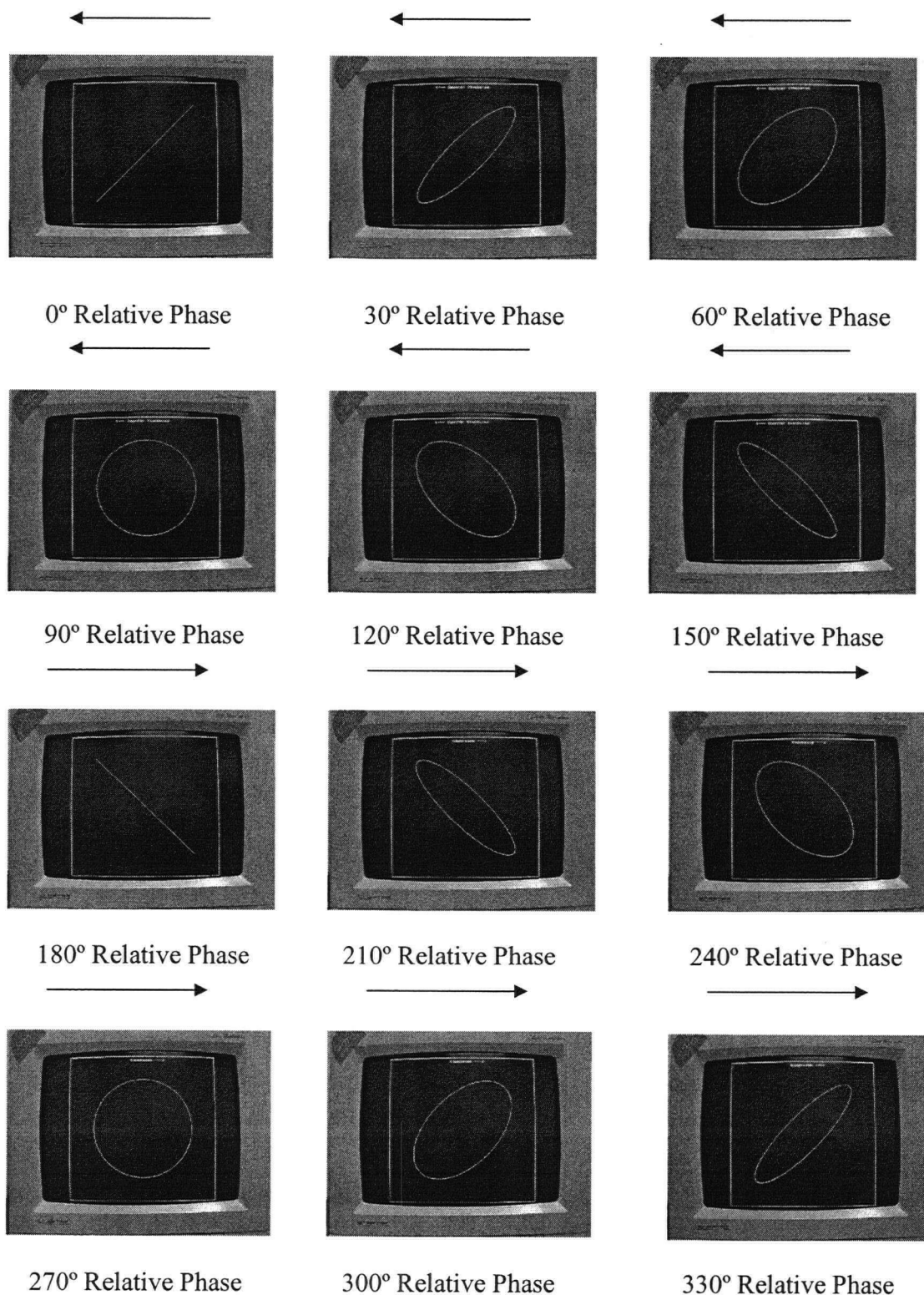
The L-S and S-S groups received the flashing square method of scanning (refer back to Figure B1). Onset of the two visual metronomes were presented at a frequency of 1 Hz. Participants received no feedback at any time during the scanning procedure. In contrast, the S-L and L-L groups received templates of the required phasing requirements in the form of a relative motion plot (or Lissajous figure) (see Figure B12). During a discrete scan, concurrent feedback was limited to the previous 500 milliseconds of movement. In addition, direction of the movement was shown at the top of the Lissajous figure by the word 'clockwise' and a right direction arrow; or the word 'counterclockwise' and a left direction arrow. A auditory metronome (1 Hz) was used for all acquisition and scanning trials in the Lissajous mode with participants instructed to complete a full cycle for each "beep" of the metronome.

Acquisition Task

The participants' goal during the acquisition session was to learn how to correctly flex and extend the arms in the horizontal plane to produce a coordination pattern of 90° relative phase (RP). All participants received 75 acquisition trials, which was broken into five blocks of 15 trials. Participants were given a maximum two-minute rest in between blocks. Depending on group assignment, acquisition trials were either performed via Lissajous figures or Flashing Squares.

Participants receiving relative motion feedback were provided a criterion template in the middle of the computer monitor (i.e., a circle). They were told that

Figure B12. A visual presentation of the Lissajous templates. There are 12 required relative phase patterns (0° to 360° in steps of 30°). The arrow represents direction of the movement (i.e., lead-lag relationship between the limbs). This represents the scanning mode referred to as 'Lissajous figures'.



the goal of the practice trials was to learn how to coordinate the limbs so that they could make continuous traces of the circle pattern on the screen. Furthermore, they were also informed that they needed to learn it well enough so that they could perform the criterion pattern from memory. Participants were instructed to complete one full cycle of movement for every "beep" of a 1 Hz metronome, with direction of movement displayed at the top of the computer screen. Provision of concurrent feedback was limited to the previous 500 milliseconds of movement.

Participants receiving the flashing square method were told that the goal of the task was to learn how to flex and extend the arms with the same time delay as demonstrated by the flashing squares. More simply, they were instructed to synchronize peak flexion of each arm with the onset of the ipsilateral flashing box well enough to be able to perform it from memory. The onset of the two visual metronomes were presented at a frequency of 1 Hz. No instructions were provided to participants concerning how to produce the criterion pattern.

Dependent Measures and Analyses

Discrete measures of relative phase were calculated for all complete cycles of movement within each trial. From each trial's calculated ranged RP values, a mean RP and standard deviation were computed. Performance of the 90° out-of-phase task was further quantified by calculating root mean square error (RMSE) relative to the criterion goal, which has been defined previously (see Experiment 1).

The dependent measure of RMSE was subjected to a 4 (group: Lissajous-Square, Lissajous-Lissajous, Square-Square, Square-Lissajous) x 4 (time: pre-scan, early acquisition, late acquisition, post-scan) ANOVA, with repeated measure on the last factor. Each value in the ANOVA consisted of a participant's average RMSE performance during three trials. Specifically, "pre-scan" consisted of the three scanning trials of 90° prior to acquisition, "early acquisition" consisted of performance on the first three trials of 90° during acquisition, "late acquisition" consisted of performance on the final three trials of 90° during acquisition and "post-scan" consisted of the three scanning trials of 90° after acquisition. All post-hoc

comparisons were performed using the Tukey HSD procedure. The level adopted for achievement of statistical significance was $p \leq .05$.

Results

Results of the repeated measures ANOVA showed a significant effect for time, $F(2, 38) = 24.22$, $p < 0.001$ and a significant time x group interaction, $F(7, 38) = 6.17$, $p < 0.001$. Post-hoc analyses of each time condition revealed the following results. No group differences were found during pre-scan or early acquisition trials. In late acquisition, both Lissajous acquisition groups (L-S and L-L) performed with significantly less RMSE than both Square acquisition groups (S-S and S-L). However, the L-S group was not significantly different than the L-L group and the S-S group was not significantly different than the S-L group. In the post-scan trials, the L-S performed with significantly more RMSE than all three other groups.

Post-hoc analyses of each group showed that both Lissajous (L-S, L-L) acquisition groups improved performance of the 90° RP, as measured by decreases in RMSE. However, a significant difference did not emerge between early and late acquisition for either Square acquisition group (S-L, S-S). These latter findings suggest that the Square acquisition groups did not learn how to coordinate the limbs in a phase offset of 90° after 75 practice trials. These results are illustrated in Figure B13 for the four experimental groups plotted as a function of time.

With respect to the different scanning procedures, post-hoc analysis revealed the following results. The L-S group did not show a significant difference from pre-scan to early acquisition. However, there was a significant difference between late acquisition and post-scan performance. The post-scan was less accurate as compared to performance in late acquisition. In contrast, the L-L group performed with significantly higher RMSE in pre-scan than all other times. No significant difference in pattern accuracy was found between late acquisition and post-scan performance (see Figure B14). Finally, no significant differences emerged between pre-scan and early acquisition for both square acquisition groups (S-S and S-L). Findings also revealed no differences between late acquisition performance and the post-scans for both groups. These data are presented in Figure B15.

Figure B13. RMSE of goal relative phase for the four experimental groups, as a function of time (early vs. late acquisition) (Error bars = SD).

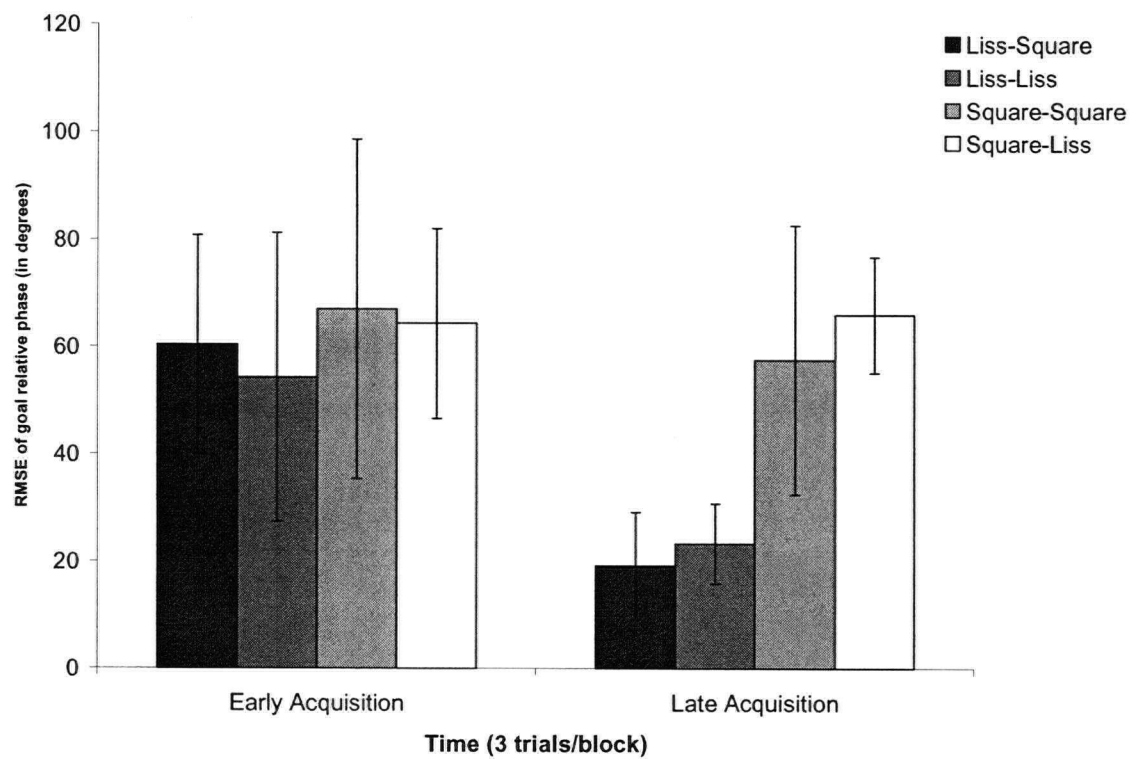


Figure B14. RMSE of goal relative phase for Lissajous learning groups, as a function of time (acquisition vs. scanning) (Error bars = SD).

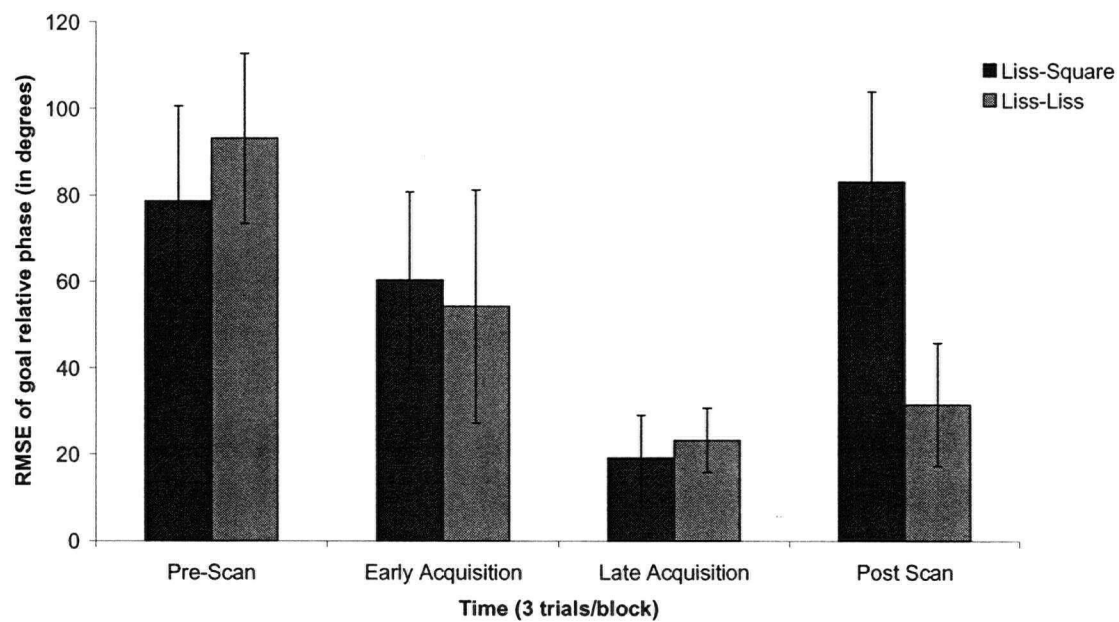
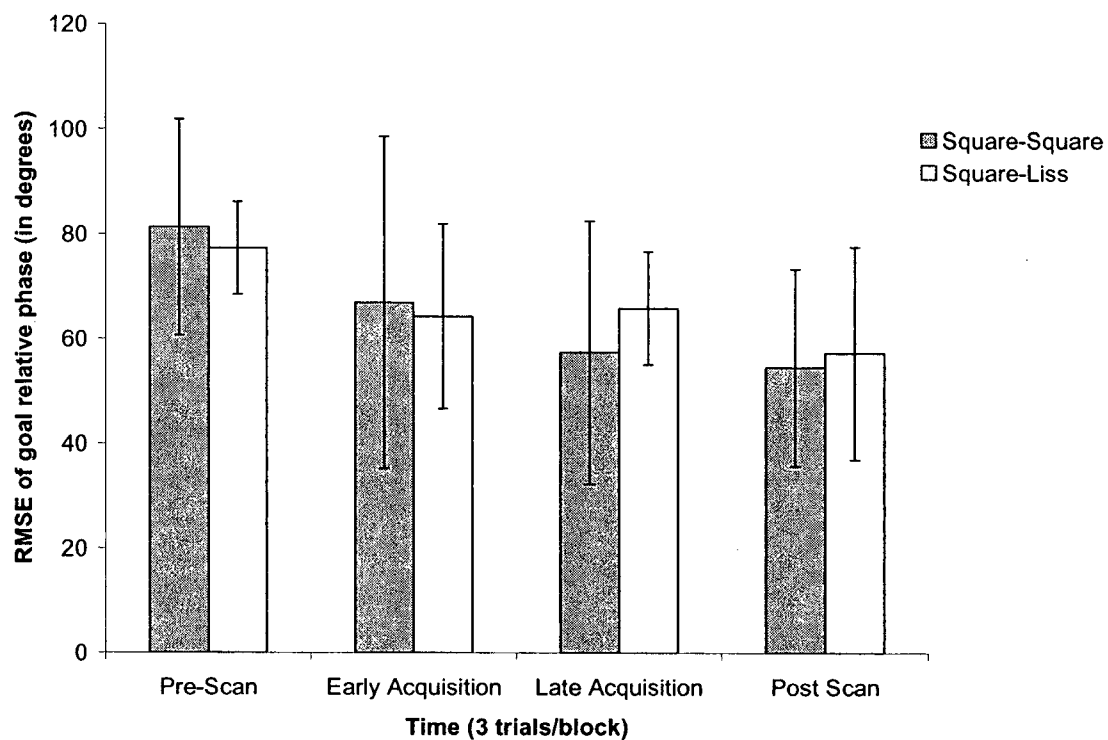


Figure B15. RMSE of goal relative phase for Flashing square learning groups, as a function of time (acquisition vs. scanning) (Error bars = SD).



Discussion

The purpose of this experiment was to assess two scanning methods used in bimanual coordination learning studies: visual metronomes in the form of flashing squares and Lissajous figures with concurrent on-line feedback. Examining trials during a pre-acquisition and post-acquisition scan, as well as trials early in acquisition and late in acquisition allowed for evaluation of the scanning methods. Performance in pre-acquisition scans was expected to be similar to early acquisition trials and performance in post-acquisition scans was expected to be similar to late acquisition trials. In addition, the experimental conditions also allowed for assessment of the two types of acquisition trials (Flashing squares and Lissajous figures).

Results showed both Lissajous acquisition groups (L-S and L-L) were able to significantly improve their performance of the new coordination pattern, shown by a significant decrease in RMSE from early acquisition to late acquisition. In contrast, the Square acquisition groups (S-S and S-L) did not appear to acquire the new coordination pattern, as there was no significant difference in RMSE from early acquisition to late acquisition. This is likely due to the fact that the Square acquisition groups did not receive any feedback regarding their performance, whereas the Lissajous acquisition groups received continuous, concurrent feedback (i.e., previous 500 milliseconds of movement).

Our data suggests that the Lissajous scan did accurately reflect the performance of the Lissajous acquisition group. Although there was a significant decrease in RMSE between the pre-acquisition scan and early acquisition trials for the L-L group, this can be explained by a learning effect from the various Lissajous scanning trials and the first few acquisition trials. Most importantly, there was no significant difference in RMSE between late acquisition and the post-acquisition scan. The performance for this group dramatically improved during acquisition and the post-scan accurately reflects this change.

In contrast, the Square scanning method does not appear to be an accurate method for evaluating participants who performed their acquisition trials via Lissajous figures. The performance of the L-S square group showed no significant

difference between pre-acquisition scanning and post-acquisition scanning, even though the group did show a significant improvement in performance during the acquisition period. In addition, the post-acquisition scanning performance reported significantly higher RMSE when compared to late acquisition performance. This implies that the Square scanning method does not accurately reflect the change in performance of participants that have learned a new coordination pattern via Lissajous figures.

Unfortunately, the results of this experiment make it very difficult to evaluate either scanning method for the Square acquisition groups. Both groups showed no significant difference in RMSE between pre-acquisition scanning and early acquisition trials, as well as no significant difference between late acquisition trials and post-acquisition scanning. However, as neither Square acquisition group significantly improved their performance of the new coordination pattern between early and late acquisition, it is impossible to ascertain if the scanning method accurately reflects the participant's coordination landscape. That is, although the scanning trials are no different than the appropriate acquisition trials, we are unable to evaluate the scanning methods as the participants did not acquire a new bimanual coordination pattern (i.e. theoretically, there should be no change in the coordination dynamics because no learning occurred).

This latter result suggests that visual flashing square metronomes, without movement-related feedback, do not provide sufficient information to acquire a new bimanual coordination pattern after 75 trials. Therefore, we decided to collect two more groups of participants ($n = 5$ per group). Participants engaged in one session of 75 practice trials. Half of the participants were scanned using the flashing square method, while the other half was scanned using relative motion feedback. Scans were employed before and after the practice trials. Once again, these were compared to early and late acquisition trials. Both groups received flashing square stimuli to learn the new coordination pattern. However, following each trial, performers also received terminal feedback in the form of a relative value phase at the top left hand corner of the screen. The participant was informed that this value represented mean relative phase for the just-performed trial.

Preliminary analysis of the data reveals that both groups improved their performance of the 90° pattern with practice. Furthermore, comparison of early and late acquisition performance with pre- and post-acquisition scanning performance reveals a difference only for the group that performed the scanning trials using flashing squares but acquired the 90° task using Lissajous figures (L-S). Although the data analysis is in its initial stages, it appears that the sensitivity of a given scanning method may be influenced by its similarity to the method of acquisition (Maslovat, Bredin, Chua, & Franks, 2004). For example, if relative motion feedback is provided for learning a new coordination pattern, it is recommended that Lissajous scanning procedures be employed to ensure a more accurate measurement of the coordination dynamics.