THE COORDINATION DYNAMICS OF CONTROL AND LEARNING IN A VISUOMOTOR TRACKING TASK

A Dissertation

by

YOUNG UK RYU

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

DOCTOR OF PHILOSOPHY

May 2007

Major Subject: Kinesiology

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Approved by:

Chair of Committee,	John J. Buchanan
Committee Members,	Charles H. Shea
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	Charles S. Lessard
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ABSTRACT

The Coordination Dynamics of Control and Learning

in a Visuomotor Tracking Task. (May 2007)

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Chair of Advisory Committee: Dr. John J. Buchanan

Two experiments were designed to examine the influence of the strength of perception-action coupling on the control and learning of a visuomotor tracking pattern. Participants produced rhythmic elbow flexion-extension motions to learn a visually defined 90° relative phase tracking pattern with an external sinusoidal signal which was set at 0.8 Hz with 8 cycles in a trial. Day 1 and Day 2 practice sessions consisted of a total of 72 practice trials. There were two visuomotor congruency groups, a congruent group with visual feedback representing the elbow's rotation and an incongruent group with feedback representing the elbow's rotation transformed by 180°. Before Day 1 practice (pre-practice) and 24 hours after Day 2 practice (post-practice), participants produced 0°, 45°, 90°, 135°, and 180° relative phase tracking patterns either with or without tracking feedback. The external signal and the limb's feedback were provided in the same workspace in Experiment 1, while both signals were provided in a separate workspace in Experiment 2. The pre-practice results demonstrated that the 0° relative phase pattern was the most accurate and stable pattern, whereas the 90° and 135°

relative phase patterns were less accurate and more variable. The incongruent group produced a more accurate and less variable 180° relative phase pattern compared to the congruent group. Practice led to a decrease in phase error and variability toward the required 90° relative phase pattern in both experiments. The congruent group produced more accurate tracking and less variable elbow amplitude compared to the incongruent group in the separate workspace, whereas no such congruency effects were found in the same workspace during practice. The post-practice results showed overall improvements in phase accuracy and stability in most relative phase patterns with practice. Overall deterioration in tracking performance was found when tracking without feedback in the pre- and post-practice sessions. These findings demonstrated that the perception-action coupling strength was modified by feedback, visuomotor mapping, perceptual pattern, and workspace framework. The differential strength of perception-action impacted the learning of the required visuomotor tracking pattern as well as the production of tracking accuracy and stability differentially among the other tracking patterns.

To My Mother and Father

ACKNOWLEDGMENTS

At this moment, I am pleased to write ‘ACKNOWLEDGMENTS’ as an obvious sign of a ‘GRADUATION’.

My big achievement owes almost everything to Dr. John Buchanan. This dissertation would be impossible if his guidance and counsel did not exist. Thank you for serving me as my advisor and training me up to be a scientist.

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CHAPTER I

INTRODUCTION

The ability to coordinate an action with an external event is essential for many everyday activities. For example, when driving a car along a road or aiming to follow a moving object, a precise temporal relationship between the movements of the limbs and the continuously changing environmental condition is required to achieve the movement goal. In many instances, the coordinated motion must be modified according to changes in the environmental event. What are the basic principles of the perception and action interaction that allow the emergence of specific spatiotemporal patterns? What are the processes that underlie the motor systems ability to learn visuomotor tracking patterns?

A dynamical systems approach to the study of voluntary movements has demonstrated that coordinative patterns emerge in a self-organizing manner (Kelso, 1981, 1984; Schmidt et al., 1990). Key signatures of a system governed by self-organizing processes are differential stability among patterns and the spontaneous change from one pattern of behavior to another referred to as pattern switching. These signatures have been found in bimanual coordination (Kelso, 1981, 1984; Carson, 1995), multijoint coordination (Kelso et al., 1991; Buchanan & Kelso, 1993), and between a limb's motion and an environmental event (Kelso et al., 1990; Wimmers et al., 1992; Byblow et al., 1995; Peper & Beek, 1998). The dynamical systems perspective suggests that the

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This dissertation follows the style of Experimental Brain Research.

acquisition of the new coordination pattern requires the addition of attractor states in the coordination landscape, and that learning takes the form of a phase transition from an unstable repeller state to a stable attractor state (Zanone & Kelso, 1992, 1997; Kelso & Zanone, 2002). The dynamical systems perspective has focused on bimanual (Zanone & Kelso, 1992; Lee et al., 1995; Fountaine et al., 1997) and multijoint coordination with regard to learning (Buchanan, 2004), but it has not yet been directed at understanding the learning processes associated with the ability to form a perception-action coupling pattern in visuomotor tracking tasks.

Incongruent information, which creates a discrepancy of information about a limb's motion and its perceived feedback, either degrades tracking performance (Smith, 1972; Tass et al., 1996; Hefter & Langenberg, 1998; Foulkes & Miall, 2000; Ceux et al., 2003; Salter et al., 2004; Salesse & Temprado, 2005) or stabilizes an unstable coordination pattern (Bogaerts et al., 2003; Roerdink et al., 2005; Tomatsu & Obtsuki, 2005; Wilson et al., 2005). Many tracking studies have also demonstrated that visuomotor performance is influenced by the spatial proximity between informational signals (Bailey, 1958; Chernikoff & LeMay, 1963; Reed et al., 2003). However, these effects of transformed visual information and spatial proximity between signals on the learning of a specific perception-action tracking pattern are largely unknown. Thus, the present studies have been designed to address the effects of visuomotor congruency and spatial proximity on learning a specific relative phase as a perception-action tracking pattern and the impact of the learning on the perceptual motor system.

CHAPTER II

REVIEW OF LITERATURE

Coordination dynamics as a theory of voluntary movements

The coordination dynamics perspective draws on the concepts of self-organization and nonlinear dynamics to explain how coordinative movements emerge under biomechanical, neuromuscular, and environmental constraints. Generally speaking, the coordination dynamic perspective stresses that movement patterns, e.g., running and walking, emerge in a self-organized way from the interaction among a system's many individual degrees of freedom (*df*). Thus, this approach emphasizes the identification of self-organizing processes, such as differential stability in coordination patterns and loss of stability leading to phase transitions, as mechanisms of control and coordination. Emphasis has been placed on understanding how biological systems spontaneously change behavior (Kelso, 1995). Self-organization as a control process refers to behavioral patterns emerging and changing without having to cognitively switch motor plans or programs, wherein patterns of coordination emerge as the result of nonlinear interactions among the systems many *df*. A key signature of a system governed by self-organizing processes is the spontaneous change from one pattern of behavior to another referred to as a phase transition. A phase transition represents a change in state of a system. This change may be from a disordered to ordered state or from one ordered state to another ordered state. Phase transitions are important because they unveil relevant control parameters and a system's order parameters or collective variables. Control parameters provide non-specific information that does not dictate the pattern that emerges, but acts to drive the system through different coordination states. Order parameters or collective variables characterize the global state of a system and change abruptly when the system exhibits a phase transition. Evidence for loss of stability underlying the phase transition is sought through a quantitative analysis of the variability present in the order parameter.

Early bimanual coordination studies conducted by Kelso (1981, 1984) demonstrated that the relative phasing (ϕ) between two limbs can distinguish different coordination patterns. Kelso (1981, 1984) required participants to produce an in-phase (both index fingers flexion-extension together) and an anti-phase (alternating flexion-extension of the index fingers) bimanual pattern as frequency of motion was increased from slow to fast. Abrupt shifts from the anti-phase to the in-phase pattern were observed at a critical movement frequency, while no transitions were observed from the in-phase to anti-phase bimanual pattern. An increase in the variability of relative phase in the anti-phase pattern occurred before the transition, a phenomenon known as critical fluctuations (Kelso et al., 1986; Schöner et al., 1986). After the transition from the anti-phase to the in-phase pattern, the variability in the relative phasing between the fingers decreased significantly. There were two main conclusions drawn from Kelso's bimanual experiments: (1) Relative phase was an order parameter because it provided a unique qualitative description of each coordination pattern and underwent a qualitative change at the transition, and (2) movement frequency was a nonspecific control parameter that induced transitions resulting from a loss of stability.

Haken, Kelso, and Bunz (1985) developed a coupled oscillator model based on Kelso's (1981, 1984) bimanual experiments. The model specified a potential function (Eq. 1) that describes the layout of the attractor states and how the layout is modified as the control parameter (movement frequency) changes. The following potential function creates wells and hills representing attractors and repellers:

$$V(\phi) = -a\cos\phi - b\cos 2\phi \qquad \text{(Eq. 1)}$$

with the ratio of a to b representing a control parameter and ϕ representing a relative phase between the coupled oscillators. Figure 1A illustrates the resulting potential function when the ratio $b/a = 1$. In the case, the wells at 0° (in-phase) and 180° (anti-phase) (closed circles) represent two attractor states and peak at 90° ($\pi/2$) (open circle) represents a 'repeller' in the system (Fig 1A). Note that the deeper well is located at 0°, representing that the 0° relative phase is a stronger attractor state than the 180° relative phase. This is consistent with the bimanual coordination patterns of in-phase and anti-phase (Kelso, 1981, 1984). As the control parameter b/a changes from 1 to 0, the potential function $V(\phi)$ is systematically altered and the well at 180° becomes shallower (Fig 1A – C). When the control parameter reaches a critical value, the attractor state at 180° disappears and a switch to the deeper well at 0° can occur if the system is perturbed (Fig 1C, D). Thus, changes of the control parameter alter the attractor

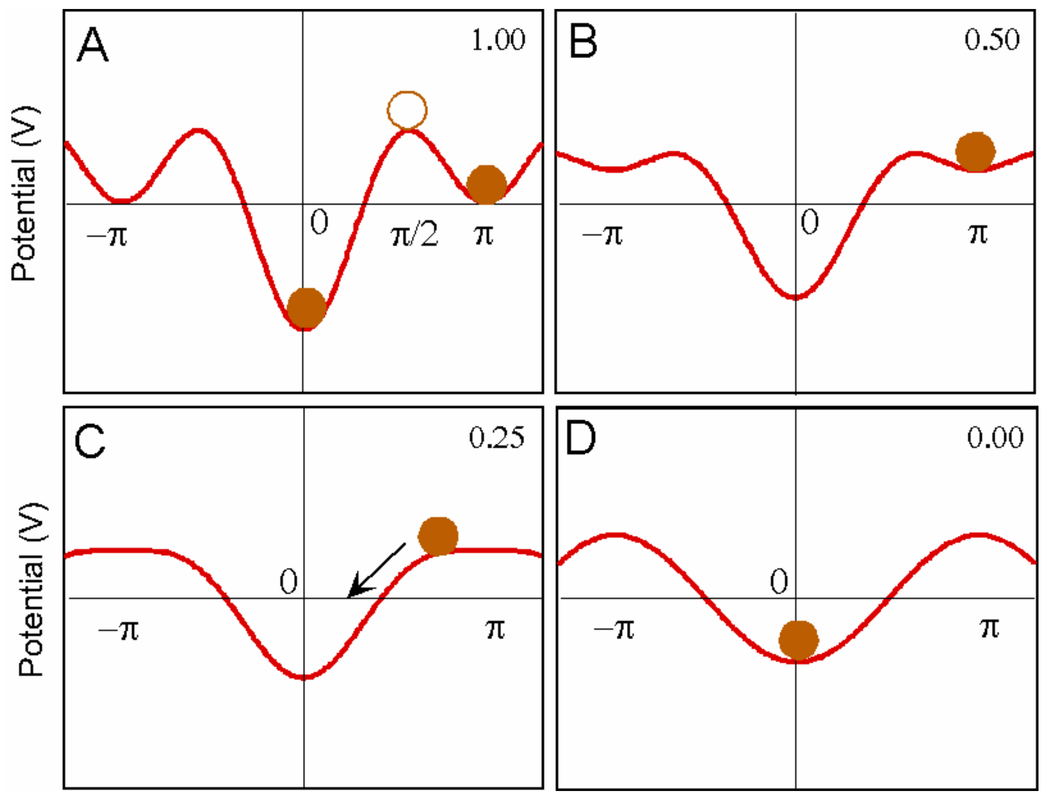

Fig 1. The HKB model of coordination. The potential (V) as the ratio *b/a* is changed. **(A)** The closed balls at 0 and π illustrate the behavior of the system initially prepared. The open ball at π/2 is a 'repeller'. **(A – D)** The phase transition is illustrated in that the closed ball at π **(A)** changes state to 0 **(D)** as the ratio *b/a* is changed.

landscape. Finally, the potential function has only one attractor state at 0° when b/a is equal to 0 (Fig 1D). A phase transition from 180° to 0° will occur when the system represented by Eq. 1 is started at the initial value of 180° relative phase, whereas a phase transition will not be observed when the system is started with the 0° relative phase requirement, which is consistent with Kelso's bimanual experiments (1981, 1984). The differential stability of movement patterns and the spontaneous phase transition as a result of loss of stability are considered key signatures of a system governed by self-organizing processes (Kelso, 1995). Similar findings based on Kelso's experiments (1981, 1984) and the HKB model have been found in a variety bimanual coordination tasks (Byblow et al., 1994; Carson, 1995; Buchanan & Ryu, 2005), and in an intralimb (within a limb) coordination task (Kelso et al., 1991; Buchanan & Kelso, 1993). Moreover, predictions of the HKB model have been extended to two person coordination tasks (Schmidt et al., 1990), and visuomotor tracking tasks (Wimmers et al., 1992; Peper & Beek, 1998).

Self-organization in visuomotor tracking

Visuomotor tracking tasks have been used to elucidate the underlying mechanisms that allow for the coordination of a movement to an environmental event (Wimmers et al., 1992; Byblow et al., 1995; Peper & Beek, 1998; Buekers et al., 2000; Liao & Jagacinski, 2000; Ceux et al., 2003; Wilson et al., 2005). The basic idea of perception-action coupling is that the perceptual and motor components are mutually related and constrained by each other. The visuomotor tracking studies conducted by Wimmers et al. (1992) and Peper and Beek (1998) have demonstrated that single limb (arm) coordination with an external signal produces differential stability of movement patterns and phase transitions from one state to another as a result of loss of stability. Wimmers et al. (1992) required participants to track a sinusoidal signal with elbow flexion and extension movements in either an in-phase pattern (external signal and elbow motion moving together in the same direction) or an anti-phase pattern (external signal and elbow movement moving in the opposite direction) with pacing frequency scaled from 1.5 Hz to 2.7 Hz in 0.1 Hz steps. The participants were not provided feedback of the limb's motion.

Results showed that the anti-phase tracking pattern was less stable than the in-phase tracking pattern. All subjects showed spontaneous phase transitions from anti-phase tracking to in-phase tracking at a critical tracking frequency, while a phase transition was not observed when starting with in-phase tracking. In a similar experimental setup, Peper and Beek (1998) also found transitions from anti-phase to in-phase tracking as a result of loss of stability. Participants were required to coordinate their wrist motion to an external signal moving horizontally in either an in-phase or an anti-phase tracking pattern with pacing frequency scaled from 1 Hz to 2.8 Hz in 0.2 Hz steps. Results demonstrated that the in-phase tracking was more stable than the anti-phase tracking, and that phase transitions from the anti-phase to in-phase were observed in 57.5% of the anti-phase trials. The phase transition phenomenon observed in these visuomotor tracking tasks may be explained by informational interactions between an environmental event and an associated effector's movement (Schmidt et al., 1990). Wimmers et al. (1992) explained the phase transition phenomenon observed in their visuomotor coordination task as follows:

> … phase transitions occur because at a particular frequency in the anti-phase mode an information resolution ceiling is reached that can be resolved by changing to the in-phase mode where, presumably, the mapping between the information provided by the visual signal (the input information) and the information generated by the in-phase movement (the output information) reduces the dimension of the informational degrees of freedom for the system. (p. 225)

In other words, at faster tracking frequencies, the visuomotor system was not able to resolve the opposite motion direction between the limb and external signal when required to produce the anti-phase pattern. Thus, phase transition from the anti-phase tracking pattern to the in-phase tracking pattern resulted from an information resolution ceiling (perceptual threshold) being reached when performing the anti-phase pattern.

Byblow et al. (1995) required participants to track either a discrete or continuous visual display with the dominant arm using forearm supination-pronation rotations in two coordination patterns, in- and anti-phase modes (in Experiment 1). Participants were asked to synchronize to the external signal (visual display) with the forearm movements in the in-phase coordination pattern, whereas participants were asked to move their forearm to the external signal in the opposite direction for the anti-phase pattern. The frequency of the visual display was scaled from 1.25 Hz to 2.75 Hz in a trial. Consistent with the previously mentioned two studies (Wimmers et al., 1992; Peper & Beek, 1998), the in-phase tracking was more stable than the anti-phase tracking, and phase transitions from the anti-phase to in-phase were observed in 17.7% of the anti-phase trials. The continuous display mode was less variable than the discrete display mode at low frequencies, but coordination patterns became unstable under both display modes at high frequencies. The authors suggested that the continuous information of the external signal served to compress variability by increasing an ability to resolve information about differences in signals at low frequencies. The ability for information resolution decreased under both display modes with increasing frequency, and did not differ at high frequencies.

The differential stability between in- and anti-phase visuomotor tracking and pattern switching from less to more stable tracking suggests common dynamic principles between bimanual and visuomotor tracking coordination tasks (Wimmers et al., 1992; Byblow et al., 1995; Peper & Beek, 1998). In bimanual coordination tasks, coupling strength between two limbs is thought to be mediated by neural transmission (Swinnen 2002). In visuomotor tracking tasks, it is proposed that the strength of the coupling between perceptual processes and action processes is dependant on coupling strength that is mediated by perceptual processing capabilities (Schmidt et al., 1990; Wimmers et al., 1992; Byblow et al., 1995; Buekers et al., 2000).

Effect of visual feedback on visuomotor tracking performance

A current trend in perception-action coupling tasks has focused on effects of visual feedback of an effector's movement in producing specific visuomotor tracking patterns (Tass et al., 1996; Hefter & Langenberg, 1998; Foulkes & Miall, 2000; Mechsner et al., 2001; Bogaerts et al., 2003; Ceux et al., 2003; Roerdink et al., 2005; Tomatsu & Obtsuki, 2005; Wilson et al., 2005). Ceux et al. (2003) examined the effect of the perception-action relation on the spatial and temporal organization of visuomotor tracking. The effects of visual feedback on actual movements were also examined. Participants were required to rhythmically rotate the elbow joint in the horizontal plane with an external signal that moved in either a horizontal or vertical direction. For the horizontally moving signal, participants were required to track it in either the same direction (horizontal in-phase) or in the opposite direction (horizontal anti-phase). For the vertically moving signal, participants synchronized their elbow flexion and extension to the bottom and top positions of the signal, respectively. All three tracking conditions were performed either with or without online visual feedback. The in-phase tracking pattern was more accurate and stable compared to the other patterns without visual feedback of the limb. When tracking with the visual feedback, the spatial accuracy did not differ between the three patterns. The online feedback of the elbow motions produced overall better spatiotemporal performance compared to without online visual feedback. These findings suggest two main conclusions. First, the same directional requirement between a motor execution and an environmental event enhances the spatiotemporal quality of visuomotor tracking patterns when tracking without feedback (Buekers et al., 2000). Second, visual feedback of an effector can enhance the spatiotemporal stability of performance of a less stable tracking pattern (e.g., an anti-phase tracking). This demonstrates the facilitator role of visual feedback of a limb's motion during tracking.

Recent studies have demonstrated that even incongruent visual information of a limb's motion during performance can stabilize coordination patterns in certain circumstances (Bogaerts et al., 2003; Roerdink et al., 2005; Wilson et al., 2005). Bogaerts et al. (2003) required participants to rhythmically perform bimanual line-drawing patterns with transformed visual feedback, which was oriented in an opposite direction (incongruent) and in the same direction (congruent) of the actual movements. Results showed that the transformed visual feedback did not influence a bimanual in-phase coordination pattern (both hands moving in- or outward together), whereas the incongruent feedback stabilized a bimanual anti-phase coordination pattern (both hands moving in the same direction) when the transformation produced a mirror image pattern. These findings show that transforming visual feedback of a limb to a perceived stable pattern (in-phase) can stabilize the production of an intrinsically less stable coordination pattern.

Similar findings were found in a unilateral visuomotor tracking task conducted by Roerdink et al. (2005). Participants in this experiment were required to track an external signal by moving the wrist joint either in-phase with the external signal (the signal and wrist joint moving in the same direction) or anti-phase pattern with the external signal (the signal and wrist joint moving in the opposite directions).

Participants could not see their wrist movements and performed under three feedback conditions: no feedback, congruent feedback (feedback representing the actual wrist motion), and incongruent feedback (the wrist motion transformed by 180°). Results revealed that the accuracy and stability of tracking was the worst in the no feedback condition, suggesting the importance of feedback in tracking performance. The incongruent visual feedback did not influence the in-phase pattern, but stabilized the less stable anti-phase pattern when the visual transformation produced a perceived in-phase pattern, consistent with findings of Bogaerts et al. (2003). Thus, the aforementioned studies demonstrate that the visual perception of the phase relationship between two objects plays a fundamental role in the stability of bimanual coordination or single limb coordination with an external event. In application, this suggests that pattern stability in motor control may increase with an increase in the strength of the perceptual coupling that can be manipulated by the relationship between the actual motion and the associated visual feedback.

More recently, Wilson et al. (2005) further examined pattern stability in a unimanual visuomotor tracking task by manipulating both the relative phasing between two visually defined oscillators and the mapping between limb motion and its output signal. Participants were required to track an external signal with a joystick movement in seven tracking conditions. The tracking task consisted of two phasing components, a visually defined relative phase and a cross-modal relative phase. The visually defined relative phase was the relative phasing between two signals displayed on a computer monitor, which included 0°, 180°, and 90° relative phase patterns. The cross-modal relative phase was defined by the phase differences between a performer's movement and the movement's visual feedback, which included 0°, 180°, and 90° cross-modal relative phases. Thus, the 0° cross-modal relative phase was a congruent mapping between a produced motion and its feedback, and the 90° and 180° cross-modal relative phases were incongruent mappings. The combination of the two components of the tracking task yielded the following tracking conditions: 0:0, 0:90, 0:180, 90:90, 180:180, 90:0, and 180:0. For example, the 90:0 condition required a performer to produce a visually defined 90° relative phase pattern with a 0° phase difference between the movement and its feedback (0° cross-modal relative phase). One of the main findings (in Experiment 1) was that the visually defined 0° relative phase patterns (0:0, 0:90, and 0:180) were more stable than the relative phase patterns with 90° and 180° cross-modal relative phases (90:90, 180:180), suggesting that producing a visually defined 0° relative phase pattern, regardless of visuomotor mapping, stabilized the actual relative phase pattern defined by the relationship between a motion and its external signal. However, this stabilization effect by the visually defined 0° relative phase patterns did not bring 0:90 and 0:180 conditions up to the stability level of the 0:0 tracking condition. The above finding shows that the visuomotor congruency (defined by cross-modal relative phase) also influences pattern stability. The results suggest that while a perceived stable pattern between two signals plays a role in increasing the strength of perception-action coupling in a visuomotor tracking task, visuomotor congruency also plays a role in determining the stability of tracking performance (Liao & Jagacinski, 2000). Thus, studies investigating the effect of visual transformation have shown that perception-action coupling strength increases with a perceived stable pattern (e.g., 0° relative phase pattern), whereas the visuomotor congruency between motor execution and its visual feedback influences the quality of performance in space and time (Buekers et al., 2000; Cunningham, 1989; Foulkes & Miall, 2000; Hefter & Langenberg, 1998; Liao & Jagacinski, 2000; Roerdink et al., 2005; Smith, 1972; Tass et al., 1996).

Visuomotor tracking with delayed feedback has been used to investigate the interaction between neuromuscular and visual systems in motor control (Foulkes & Miall, 2000; Hefter & Langenberg, 1998; Smith, 1972; Tass et al., 1996). Smith (1972) had participants track a circle (20 cm in diameter) and an octagon (19 cm on a side) under eight different delays of temporal visual feedback of the participants' tracking (0, 17, 50, 80, 120, 220, 420, and 820 msec). The author measured tracking accuracy (time on target) and examined the relationship between the delayed time and tracking accuracy. Results demonstrated that decrements in performance occurred as delay time increased. This finding suggests that increased delays between a motion and its visual feedback degrade motor performance. Work by Tass et al. (1996) showed that delay-induced transitions occur in a visually guided tracking movement. In the study participants were required to track a sinusoidal signal (set at an individual's preferred frequency) with delayed visual feedback of the participants' tracking signals. The results demonstrate that increasing the delay time of feedback induced behavioral changes in tracking. In other words, participants produced a stable tracking pattern characterized by well defined relative phase relationships between two signals without any delay.

With an increase in delay time, tracking behavior changed from a chaos like pattern (a fluctuated phase relationship between two signals) to a drift pattern (slower tracking signal to the external signal). Taken together, these delay feedback studies clearly have demonstrated that a discrepancy between visual and proprioceptive feedback degrades tracking performance.

Liao and Jagacinski (2000) had participants perform sinusoidal tracking of a pursuit and compensatory display using both position and velocity control. The pursuit tracking required performers to produce a 0° phase relationship between the external signal and the performer's tracking signal. The compensatory tracking condition provided an error of current tracking performance so that performers were required to move their motion in the opposite direction of the displayed error. The position and velocity controls were characterized by 0° and 90° phase differences, respectively, between the performer's motion and its output signal. Therefore, combinations of tracking type (pursuit and compensatory) and control type (position and velocity) yielded four tracking conditions. For example, the pursuit/velocity condition required performers to produce the 0° phase relationship between the external signal and the performer's tracking signal with the 90° phase difference between the performer's movement and its output signal. Results showed that the compensatory tracking with velocity control was the least stable of the tracking conditions, with the weaker perception-action coupling in the compensatory tracking impacted by the incongruent mapping (90° relative phase) of the output signal. This study suggests that pattern stability can be influenced by the visuomotor congruency between an effector's movement and its output signal.

Recently, Salesse and Temprado (2005) had participants produce an in-phase pattern (right wrist and ankle moving in the same direction, isodirection pattern) or an anti-phase pattern (right wrist and ankle moving in the opposite direction, non-isodirection pattern) under congruent and incongruent visual feedback conditions. The visual feedback was displayed correctly for the movements during the congruent condition, while the visual feedback for one of two limbs was transformed by 180° during the incongruent condition. For example, when producing the in-phase pattern the congruent feedback was displayed in an isodirection format and the incongruent feedback was displayed in a non-isodirection format. A metronome paced the movement from 1.25 Hz to 2.5 Hz in 0.25 Hz steps. Results demonstrated that the produced pattern was more stable in the congruent feedback (isodirectional presentation) than in the incongruent feedback for the in-phase pattern. For the anti-phase pattern, however, performance was more stable in the congruent feedback condition (non-isodirectional presentation), inconsistent with Bogaerts et al.'s findings (2003, also Roerdink et al., 2005). These results demonstrated that the transformed visual feedback destabilized the performed coordination patterns, suggesting that visuomotor congruency was the primary factor in determining pattern stability in their hand-foot coordination task.

When learning to track, it has been shown that a congruent visuomotor mapping will enhance tracking accuracy during practice compared to an incongruent visuomotor mapping or delayed mapping (Carnahan et al., 1996; Grafton et al., 2001). Carnahan et al. (1996) required participants to learn a pursuit tracking of a signal (red square) with a hand-hold mouse. The signal moved at a constant velocity up and down on the computer screen in a vertical path. In experiment 1, visual feedback (open square) produced by a participant was provided either immediately (0 delay) or with a 333 msec delay. During practice, the 0 delay group performed with less error compared to the 333 delay group. In experiment 2, the authors added more delay groups: 83 msec, 167 msec, 250 msec, and 417 msec delays. The main finding from experiment 2 was that tracking error increased as the internal delay increased. These findings suggest that an incongruent mapping between the limb's motion and its visual feedback degrades the accuracy of tracking performance.

Grafton et al. (2001) required participants to learn pursuit tracking of an external signal (a visual dot) which continuously moved in the horizontal direction. There were two kinds of trials, sequence and random. In random trials, the external signal reversed direction at randomly generated screen positions. In sequence trials, the external signal reversed direction at points determined by a sequence. Participants were assigned to a random, perceptual, motor, or identical group. The identical group practiced with a compatible visuomotor mapping between a limb's motion (joystick motion) and its visual feedback. The other three groups practiced with an incompatible mapping represented by a 180° reversed joystick motion to the visual feedback. In a transfer test after practice, the practiced sequence was reintroduced with respect to the pattern of external signal movements for the perceptual group or with respect to hand movements for the motor group. The random group always practiced with random trials during practice. Participants practiced a total of 28 trials with trials 10 through 27 for the sequence trials and the other trials for the random trials. After practice, all four groups had a transfer test with compatible mapping. Results demonstrated that the compatible mapping condition (identical group) produced better tracking accuracy compared to the incompatible mapping condition (perceptual and motor groups) during practice. In the transfer test, the perceptual group produced similar performance to the identical group, suggesting positive transfer. The motor group did not demonstrate transfer because the motor group did not look different from the random group at transfer. These findings suggest that (1) an incongruent visuomotor mapping between the limb's motion and its visual feedback degrades accurate tracking, and (2) that task specific learning occurs mostly at the perceptual level compared to the motor level.

Learning a coordination pattern and evolution of the attractor dynamics

Motor learning has been investigated from a dynamical systems perspective over the past 15 years (Zanone & Kelso, 1992, 1997; Lee et al., 1995; Kelso & Zanone, 2002; Buchanan, 2004; Buchanan et al., 2007). This perspective emphasizes the identification of the system's intrinsic dynamics prior to practicing a specific coordination pattern (Zanone & Kelso, 1992, 1997). Figure 1A portrays the HKB model potential function representing the intrinsic bistable regime of in-phase and anti-phase. The relative stability of the two attractors at 0° and 180° (closed circles) is represented by the depth of each well, and the strength of their attraction by the slope of the curve. The 90° relative phase (open circle) is a repeller in the landscape (Fig 1A). In order to transform the 90° relative phase into an attractor state, extensive practice is required to overcome the attraction of the intrinsic dynamics (Zanone & Kelso, 1992, 1997; Lee et al., 1995; Kelso & Zanone, 2002).

According to the dynamic pattern perspective, the learning of a new coordination pattern is influenced by existing attractor states (in- and anti-phase) and involves the establishment of a new attractor state (Zanone & Kelso, 1992, 1997). To investigate the intrinsic attractor states and the establishment of a new attractor associated with learning, a scanning procedure has been used to evaluate a learner's motor capacities before, during and after practice (Zanone & Kelso, 1992, 1997; Lee et al., 1995; Fountaine et al., 1997; Kelso & Zanone, 2002; Buchanan, 2004; Buchanan et al., 2007). For example, Zanone and Kelso (1992, 1997) had participants produce relative phase values between the index fingers that ranged from 0° to 180° in 15° steps, with two visual metronomes representing the required relative phase pattern. The scanning procedure revealed that the 0° (in-phase) and 180° (anti-phase) patterns were stable fixed point attractors of the bimanual coordination landscape, and that the 90° relative phase pattern was a repeller in the bimanual coordination landscape. The results were consistent with previous scanning experiments (Yamanish et al., 1980; Tuller & Kelso, 1989) and the predictions of the HKB model of bimanual coordination (Haken et al., 1985).

Experiments conducted by Zanone and Kelso (1992, 1997) were seminal works in illustrating the dynamic systems approach to the study of motor learning. In Zanone and Kelso's study (1992, also 1997), participants practiced a 90° relative phase pattern between two index fingers for five days. During practice trials, participants were spontaneously observed to exploit features of the two stable relative phase patterns, in- and anti-phase, when practicing the required 90° relative phase pattern. Thus, learning the 90° relative phase pattern emerged in relation to the system's intrinsic dynamics, suggesting that learning resulted from a competition and/or cooperation among the preexisting or preferred coordination patterns (Zanone & Kelso, 1992, 1997; Lee et al., 1995; Kelso & Zanone, 2002). A post-practice scanning test revealed that an attraction towards the 90° relative phase pattern was developed with a significant reduction in variability compared to the pre-practice scanning trials, which suggests that participants learned to produce the 90° relative phase pattern. In the Zanone and Kelso's study (1992, also 1997), the result of post-practice scanning tests compared to that of the pre-practice scans demonstrated that the relative phase patterns near the 90° relative phase pattern were now attracted toward the 90° relative phase pattern. The above findings show that the 90° relative phase had become a stable fixed point attractor of the bimanual coordination landscape. Moreover, the acquisition of the novel 90° relative phase pattern resulted in a decrease in the stability of the 180° relative phase pattern. The authors argued that the initially less stable 180° pattern lost stability as the strength of the memory for the 90° relative phase pattern increased. Thus, the comparison between the pre- and post-practice scanning trials revealed that the entire attractor layout qualitatively changed with learning. Taken together, these findings suggest that learning a new coordination pattern takes the form of a phase transition that can modify the entire coordination landscape (Buchanan, 2004; Kelso & Zanone, 2002; Zanone & Kelso, 1992, 1997).

Lee et al. (1995) required participants to learn a 90° relative phase pattern between the right and left arm with different amplitude requirements in each arm (left arm = 60°, right arm = 90°). The participants practiced the required pattern for three consecutive days (a total of 60 practice trials). Test trials (an abbreviated scanning probe) were performed of an in-phase (0° relative phase), an anti-phase (180° relative phase), and the required 90° relative phase patterns before, during and after practice. Results showed that early in practice, the participants had tendencies to produce either an in-phase or an anti-phase pattern when attempting the required relative phase pattern, and participants produced equal amplitudes for both the left and right arms. Later in practice the participants produced the required relative phase pattern with less variability and increased accuracy of the 90 relative phase and required amplitude value. These findings suggest that the learning of a new coordination pattern is a process of breaking down a preexisting coordination tendency in space and time. Test trials after practice showed that equivalent variability among the three relative phase patterns was achieved, suggesting that learning the 90° relative phase pattern stabilized all possible relative phase patterns as well as the required pattern.

Buchanan (2004, see also Buchanan et al., 2007) investigated learning an intralimb (within a limb) coordination pattern from the dynamical systems perspective.

The task required participants to learn a 90° relative phase pattern between the elbow and wrist for five consecutive days (a total of 180 practice trials). Test trials (an abbreviated scanning probe) were performed of the in-phase (0° relative phase), anti-phase (180° relative phase), and the required 90° relative phase patterns before, and after practice. Test trials before practice demonstrated that the 90° relative phase pattern was not a stable attractor of the elbow-wrist coordination landscape. After five days of practice, however, the variability of the 90° relative phase pattern decreased significantly. Test trials after five days of practice also revealed equal levels of stability among the three relative phase patterns, consistent with Lee et al. (1995). These results support the conclusion that learning the 90° relative phase pattern between the elbow and wrist took the form of a phase transition whereby a repeller was stabilized with practice, consistent with numerous bimanual studies (Zanone & Kelso, 1992, 1997; Lee et al. 1995; Fontaine et al. 1997; Kelso and Zanone, 2003).

Effect of display proximity in visuomotor tasks

Many scientists and engineers have examined the effect of display mode to investigate human visuomotor control and to develop ergonomically designed devices (Poulton, 1974). As previously reviewed, Byblow et al. (1995) demonstrated that information display can alter the strength of perception-action coupling and impact the quality of coordination patterns. Another issue in the present study is the impact of display proximity in producing a coordination pattern. Display proximity in the present study refers to how close together two signals in space are when producing a required tracking pattern. Two signals will have close proximity if they appear in the same window or are displayed in an integrative way (Wickens and Carswell, 1995).

Bailey (1958) investigated the effect of display modes in hovering a simulated helicopter. This study examined 3 different display modes, a conventional display system, an integrated system, and a quickened system. While altitude information and groundspeed information were presented as a separate item of information in the conventional display system, altitude information was transferred to the groundspeed indicator in order to provide an integrated display. In the quicken display mode, the altitude rate for both the lateral and longitudinal coordinates were summed to the groundspeed signal in a single display indicator, and the altitude reference line was eliminated. Participants were required to learn the relationship between their control, the altitude display, and the groundspeed display in hovering performance. Results demonstrated that hovering performance was the best with the quicken display mode and the worst with the conventional mode.

Chernikoff and LeMay (1963, see also Sampson & Elkin, 1965; Fracker & Wickens, 1989) investigated the interactions of control and display in a visuomotor tracking task. The authors required participants to perform a 2-dimensional (x and y axes) compensatory tracking task with the following 4 display_control conditions, one-dot_one-stick, one-dot_two-stick, two-dot_one-stick, and two-dot_two-stick. The one-dot was an integrated display of information in combining x and y coordinate axes together and the two-dot was separate tracking information in that each dot represented each coordinate axis. The one-stick was an integrated control moving 2-dimensionally, and the two-stick was a separated control in that one stick controlled the x axis motion and the other stick controlled the y axis motion. In addition, position and acceleration output signal dynamics were applied to either both axes equally or each axis differently. The position dynamics represented a participant's output signal without any manipulation of it, representing a congruent visuomotor mapping. The acceleration dynamics were acquired by taking the second derivative of a participant's output signal, representing an incongruent visuomotor mapping. The one-dot_one-stick condition was the conventional 2-dimensional compensatory tracking task. The task goal was to reduce tracking error. Results demonstrated that the integrated display (one-dot) was better regardless of the controls when the same dynamics were used in both coordinates. When different dynamics were used for each coordinate, the display modes did not impact on the tracking performance, and the two-dot_two-stick condition produced the best performance.

Reed et al. (2003) investigated the effect of manipulating the visual display by separating the external signal from the tracking signal during one dimensional visuomotor tracking. Participants were required to track a horizontally moving signal (dot) with a joystick movement in five separation conditions. The external signal was always presented at the middle level of the screen, while the joystick cursor was positioned at the external signal level (Gap 0), 4.5 cm (3.2° retinal eccentricity of participant's eyes) above (Gap +1) and below (Gap -1), and 9.0 cm (6.4°) above (Gap +2) and below (Gap -2). Participants were asked to focus their eyes on the external signal, and minimize eye movements. Results showed that tracking performance was the most accurate when both signals were at the same level, and that the increase in signal separation reduced accuracy significantly.

As reviewed, the degree of spatial proximity can determine the strength of perception-action coupling and impact the visuomotor performance. Wickens and Carswell (1995) suggested that "… closeness in space … will generally make their [signals] comparison and integration easier because of the decrease in visual search cost and time to go from one to the other." This implies that the presentation of signals closely in space will produce a perceptually strong workspace due to ease of comparison and integration between the signals by reducing visual search cost, whereas presenting signals spatially away from each other would produce a perceptually weak workspace to perform.

Learning a visuomotor tracking task

The visual feedback transformation studies have focused on the short term adaptation of coordination performance (Bogaerts et al., 2003; Ceux et al., 2003; Roerdink et al., 2005; Tomatsu & Obtsuki, 2005; Wilson et al., 2005). Although an incongruent visuomotor mapping degrades tracking accuracy during practice compared to a congruent visuomotor mapping (Carnahan et al., 1996; Grafton et al., 2001), few studies have addressed how transformed visual information contributes to the learning of a specific visuomotor tracking pattern (e.g., 90° relationship between a an external signal and a limb motion) and its impact on the whole perceptual motor system. The purpose of the present study was to address the effect of visuomotor congruency on learning a specific relative phase pattern in a rhythmic unimaual visuomotor tracking task. In order to test the effects of visuomotor congruency, two forms of visual feedback of the elbow movement were utilized: congruent feedback (representing the movement as made) and incongruent feedback (feedback transformed by 180°), with both congruency conditions required to learn the same visually defined relative phase pattern.

Many visuomotor tracking tasks have been performed in a form of a pursuit tracking to an external signal that was characterized by a 0° relative phase relationship between the external signal and the tracking motion. Several pursuit tracking tasks characterized by a 180° relative phase relationship (two components moving in opposite direction) have been used to investigate the strength of the perception-action coupling and pattern stability (Buekers et al., 2000; Peper & Beek, 1998; Roerdink et al., 2005; Wilson et al., 2005; Wimmers et al., 1992). However, relative phases between the external signal and the tracking movement other than 0° and 180° relative phases have received little attention in the visuomotor tracking literature besides a study conducted by Wilson et al. (2005). Learning of a specific coordination pattern that was an intrinsically less stable pattern (e.g., 90° relative phase pattern) has been investigated in intralimb and interlimb tasks in order to investigate the impact of practice on the intrinsic coordination dynamics (Zanone & Kelso, 1992, 1997; Fountaine et al., 1997; Smethurst & Carson, 2001; Kelso & Zanone, 2002; Buchanan, 2004). Thus, in order to identify the learning processes of a less stable visuomotor tracking pattern and its impact on the visuomotor tracking system, the present study required participants to learn a visually defined 90° relative phase pattern between an external signal and the online visual feedback of a limb's motion. Five visuomotor tracking patterns, 0°, 45°, 90°, 135°, and 180° were employed in a scanning procedure to identify the intrinsic dynamics of the visuomotor tracking system and the learning processes underlying visuomotor tracking capabilities.

To test the effects of visuomotor congruency, two forms of visual feedback of a limb's motion were utilized: congruent feedback (feedback representing the movement as made) and incongruent feedback (feedback transformed by 180°). Both congruency conditions were required to produce the same visually defined relative phase pattern. Since the visual manipulation of a perceived symmetric pattern stabilized an unstable coordination pattern (Bogaerts et al., 2003; Roerdink et al., 2005; Tomatsu & Obtsuki, 2005; Wilson et al., 2005), it is reasonable to hypothesize that visuomotor congruency will interact with the system's intrinsic dynamics with distinct attractor landscapes for each the congruency group. It is also hypothesized that learning of a novel tracking pattern will influence the whole visuomotor tracking system's dynamics. Thus, practice of a specific behavioral demand will affect not only the required coordination pattern, but also the entire coordination dynamics (Schoner et al., 1992; Zanone & Kelso, 1992).

In Experiment 1, the external signal to be tracked and visual feedback of the limb's motion were provided in the same workspace to learn the required 90° relative phase tracking pattern. Previous studies showed that visuomotor congruency influenced the spatiotemporal quality of coordination performance in that a congruent feedback was superior to an incongruent feedback in visuomotor tasks (Liao & Jagacinski, 2000; Grafton et al., 2001; Wilson et al., 2005). Based on the spatial proximity idea (Wickens & Carswell, 1995), however, the overlapping display in Experiment 1 might provide perceptually strong information in that performers possibly utilize the distance between the slope of the external signal and the slope of the limb's feedback. This benefit of the overlapping display might reduce the effect of incongruent visuomotor mapping to make the comparison easier between the external signal and the limb's signal. Thus, the overlapping of the two signals in the same workspace will benefit the incongruent group in learning the required phase relationship between the external signal and the limb's motion.

In Experiment 2, the external signal to be tracked and the limb's feedback were provided in a separate workspace. The idea behind the workspace manipulation was that presenting two signals in separate workspaces will make them difficult to perceive and compare, compared to the overlapping display mode (Experiment 1) (Wickens & Carswell, 1995). The signals separation in space should increase the visual search cost between the two signals and the incongruent information between visual and proprioceptive feedback will degrade tracking performance. Taken together, these workspace modes might impact on the perception-action coupling and influence quality of performance in the present visuomotor tracking task. It is hypothesized that the degree of learning will be slightly different or even between the two congruency groups in the overlapping display mode (Experiment 1), whereas it will be distinct between the groups with an advantage for the congruent group in the separate display mode (Experiment 2).

CHAPTER III

EXPERIMENT 1

Methods

Subjects

A total of twelve students (6 males and 6 females, mean age = 22.2 yrs) volunteered to participate in the study. The experimental protocol and consent form were approved by the IRB board of Texas A&M University and all participants voluntarily signed the consent form prior to the experiment. All participants were self-reported right handers and had normal or corrected-to-normal vision.

Apparatus

Participants sat on a height-adjustable chair and faced a computer monitor located 0.76 meters to the front of the participants. The participant's right elbow was comfortably placed on a table in a supine position. Participants placed the longitudinal axis of their upper arm at about 45° to the surface of the table (Fig 2A). Participants wore a wrist orthosis to secure their wrist joint in parallel with the longitudinal axis of the forearm. A wall (0.84 m × 0.48 m) was mounted on a table between the participants' face and the participants' elbow so that participants could not see their forearm motions (Fig 2A).

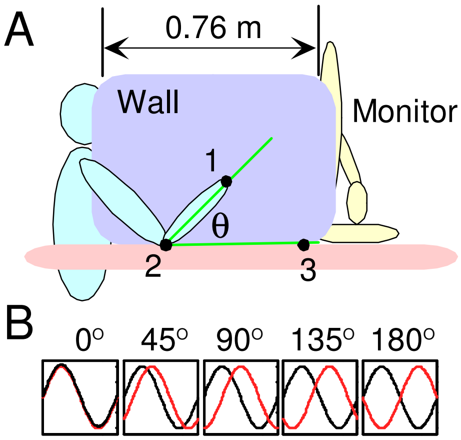

Fig 2. (A) Setup of the present tracking experiment and **(B)** the required target patterns. **(B)** The black curve represents the external signal and the red curve represents the required signal that a participant is supposed to produce.

The computer monitor was used to display the external tracking signal, the online feedback of the participant's tracking motion, and an angle-angle plot of the tracking signal vs. the limb's motion. The sinusoidal tracking signal was produced with an AFG320 arbitrary function generator (Tektronix®, SONY). The oscillation frequency was set at 0.8 Hz with a total of 8 cycles in a trial. An OPTOTRAK® 3020 3D camera (Northern Digital) recorded the position of infrared light emitting diodes (IREDs). The OPTOTRAK® 3020 is a pre-calibrated 3D motion-detecting system consists of three lens assemblies. Each lens has a 34° × 34° field of view, with the 3 lens precalibrated to a resolution of 0.1 mm in the x (mediolateral) and y (vertical) directions and 0.15 mm in the z (anteroposterior) direction at a distance of 2.5 meter. Three IREDs were mounted as follows: 1) attached to a dowel held in the hand, 2) lateral epicondyle of the elbow, and 3) on the table corresponding to the dowel's height when the participant's hand was extended to maximum extension along the table (Fig 2A). The participant's elbow angular motion was represented by the change in the angle ϴ between the endpoint's position (the dowel) with regard to the table (Fig 2B).

Task and procedures

Each participant was randomly assigned to an experimental group based on visuomotor congruency: (1) a congruent group (CON) with visual feedback information representing the elbow's rotation and (2) an incongruent group (INC) with visual feedback information representing the elbow's rotation transformed by 180°. For the congruent group, rotation of the forearm upward (flexion) produced an upward motion of the elbow angle on the screen. For the incongruent group, rotation of the forearm upward (flexion) produced a downward motion of the elbow angle on the screen. The angle ϴ approached 0° when the elbow was fully extended. The angle increased positively with flexing the elbow in the congruent condition. In the incongruent condition, the angle decreased negatively with flexing the elbow since the online visual feedback was multiplied by -1 during a trial. The range for the required elbow motion was from 18° to 79°. Thus, the required joint amplitude corresponding to the external sinusoidal wave was 61°. Participants were provided both the external sinusoidal signal and the online visual feedback of the elbow's rotation overlapped in the same workspace (Fig 2B). The workspace was 14 cm (length) × 4.5 cm (height), and presented two cycles of the external signal during a trial. Participants were required to learn to rhythmically coordinate the flexion-extension movement of the elbow with the sinusoidal signal at a 90° relative phase relationship.

Participants were given 4 tracking trials to familiarize themselves with the production of the joint motion displayed on the computer screen. Participants were asked to track the external signal in both a 0° relative phase (two signals moving together) and a 180° relative phase (two signals moving in the opposite direction) visuomotor pattern. For these trials, the oscillation frequency was set at 0.5 Hz with a total of 8 cycles in a trial. This oscillation frequency was slower than the one used in the experimental sessions (0.8 Hz) to reduce any practice effect with the tracking frequency for the experimental sessions. Participants were informed of the visuomotor congruency relationship during these familiarization trials.

Scanning sessions

The pre-practice scanning session was conducted prior to the practice of the 90° relative phase pattern on day 1, and the post-practice scanning session was conducted on day 3 without any following practice trials. The scanning sessions consisted of 3 trials for 5 different relative phase patterns: 0°, 45°, 90°, 135°, and 180° (Fig 2B). The relative phase patterns were defined by the relationship between the online visual feedback of the elbow motion and the external signal. Before performing each relative phase pattern, the required relative phase pattern was shown to a participant (Fig 2B). The external signal was represented with a black trace while the signal that the participants were supposed to reproduce with elbow motion was represented with a red trace. The assigned participant's signal lagged the assigned external signal in the 45°, 90°, and 135° relative phase pattern (Fig 2B). Participants were instructed to watch the pattern represented by the two external signals and to try to reproduce the pattern when they performed the scanning trials. The oscillation frequency for the scanning trials was set at 0.8 Hz with a total of 8 cycles per trial. The oscillation frequency of 0.8 Hz was chosen because previous tracking studies have shown that multistability was observed around at 0.8 Hz (e.g., 0.67 Hz in Ceux et al., 2003, 1 Hz in Buekers et al., 2000). After watching one of the relative phase patterns, participants immediately performed 3 consecutive trials for the assigned relative phase pattern. The five relative phase patterns were performed in a random order. The scanning sessions consisted of a feedback condition (F) and a no feedback condition (NF). In the feedback condition the elbow angle trajectory was plotted, and in the no feedback condition the elbow angle was not presented with the tracing signal. The feedback condition was conducted first and the no feedback condition was conducted after the feedback condition in every scanning session. The angle-angle plot was not provided for the scanning sessions.

Practice sessions

The practice session was initiated after the scanning trials. Practice sessions 1 (day 1) and 2 (day 2) consisted of 6 trials per block which yielded 36 practice trials per session (a total of 72 practice trials). Participants were required to coordinate rhythmic elbow flexion-extension movements to a continuous sinusoidal wave at a 90° relative phase relationship. The elbow angle trajectory was provided concurrently with the external sinusoidal signal in every trial. After an odd numbered trial, both the re-play of the performed trial and its angle-angle plot (tracking signal vs. elbow angle) were provided as terminal feedback. Participants were informed that a circle in the angle-angle plot represented the required 90° relative phase relationship between the tracking signal and the participant's elbow motion. The angle-angle plot provided a continuous feedback display that was more consistent with the task display than a static error score. For this reason, the angle-angle plot was used as a form of terminal feedback and to facilitate learning.

Data analysis

Prior to any data analysis, the 3D IRED trajectories were filtered with a dual-pass Butterworth Filter with a cutoff frequency of 10 Hz. The filtered data were used to compute the elbow joint angle. The first cycle of motion was dropped and considered as an adaptation phase so that 7 cycles were analyzed from each trial.

Mean relative phase and phase variability

A continuous relative phase was computed to characterize the phase relationship between the external signal and the elbow angle trajectory. The observed continuous relative phase was calculated as $\phi_{obs} = \Theta_{elbow} - \Theta_{external}$. For each signal i, individual phase angles were computed as, $\Theta_i = tan^{-1}\ [(dx_i/dt)/x_i]$, with x_i the normalized position and dx_i/dt the normalized instantaneous velocity. An observed continuous relative phase of ϕ_{obs} = 0° represents no phase difference between the external signal and the elbow angle trajectory, while a value of ϕ_{obs} = 180° characterizes two signals that move in exact opposite directions. A value of ϕ_{obs} = -90° represents the elbow signal lagging the external signal and a value of ϕ_{obs} = 90° (-270°) represents the elbow signal leading the external signal. A relative phase mean and standard deviation (ϕ_{SD}) were computed for each trial and all relative phase means reported are based on absolute values. An absolute relative phase error ($\phi_{AE} = |\ \phi_{req} - \phi_{obs}\ |$) was computed and this score was used to evaluate visuomotor tracking accuracy and learning. The relative phase standard deviation (ϕ_{SD}) provided a measure of visuomotor pattern stability.

Joint amplitude

The elbow's angular time series was used to compute joint angular displacement. A peak picking routine located the points of maximum flexion and extension in the elbow's angular time series. The peak angle values were used to compute half cycle angular displacements for the elbow joint for every cycle in a trial. A standard deviation of joint amplitude was calculated for each trial in order to measure amplitude variability.

Tracking frequency

The time values were used to compute tracking duration (TD) as the time between every two successive peaks in a trial, $TD = peak_{i+1} - peak_i$. TD values were used to compute tracking frequency (TF) as follows, $TF = 1/TD$. A mean tracking frequency was calculated for each trial.

Statistical analysis

The main dependent variables were absolute phase error (ϕ_{AE}), phase variability (ϕ_{SD}), joint amplitude, amplitude variability, and tracing frequency. All five variables from the pre-practice scanning session were analyzed in a 2 Congruency (CON, INC) × 2 Feedback (F, NF) × 5 Visuomotor tracking pattern (0°, 45°, 90°, 135°, 180°) ANOVA with the last two variables repeated measures. The practice session data were analyzed in 2 Congruency × 2 Day (day 1, day 2) × 6 Block (1, 2, 3, 4, 5, 6) ANOVA with the last two factors repeated. To check for practice effect, comparisons between pre- and post-practice scanning sessions were performed separately for each relative phase pattern, and analyzed in 2 Congruency × 2 Feedback × 2 Session (pre-practice, post-practice) ANOVAs with the last two variables as repeated measures. Duncan's multiple range test was used to analyze all post-hoc main effects, and simple main effect tests were performed to reveal any significant interactions. All statistical significance was set at $\alpha < .05$. Distributions around the scanned RP visuomotor tracking patterns from the preand post-practice scanning sessions were determined with the bandwidth set at ±22.5° for each scanned pattern. The distribution data were analyzed with a 2 Congruency × 2 Band (within ±22.5°, outside of ±22.5°) and a 2 Feedback × 2 Band chi-square test.

Results

Pre-practice scanning

General characteristics of relative phase patterns

Inspection of Figure 3A shows that in the pre-practice scanning session, the most consistent visuomotor tracking occurred in the 0° and 180° relative phase conditions for both congruency groups. The other three relative phase patterns were characterized by either inconsistent cycle-to-cycle motion or attraction to the 0° or 180° patterns. Figure 3B displays the individual trial relative phase means from the pre-practice scanning session. Required relative phase values for the 5 scanned patterns were 0°, -45°, -90°, -135° and ±180°. The negative values represent that the task required elbow motion to lag the external signal. In the feedback condition (circles), the most clustering occurred for the 0° relative phase pattern followed by the 180° relative phase pattern. Thus, 0° and 180° represent intrinsically stable attractors of the visuomotor tracking system. In the no feedback condition (triangles), a dense clustering was found only for the congruent group when producing the 0° relative phase pattern. (Fig 3B). In both

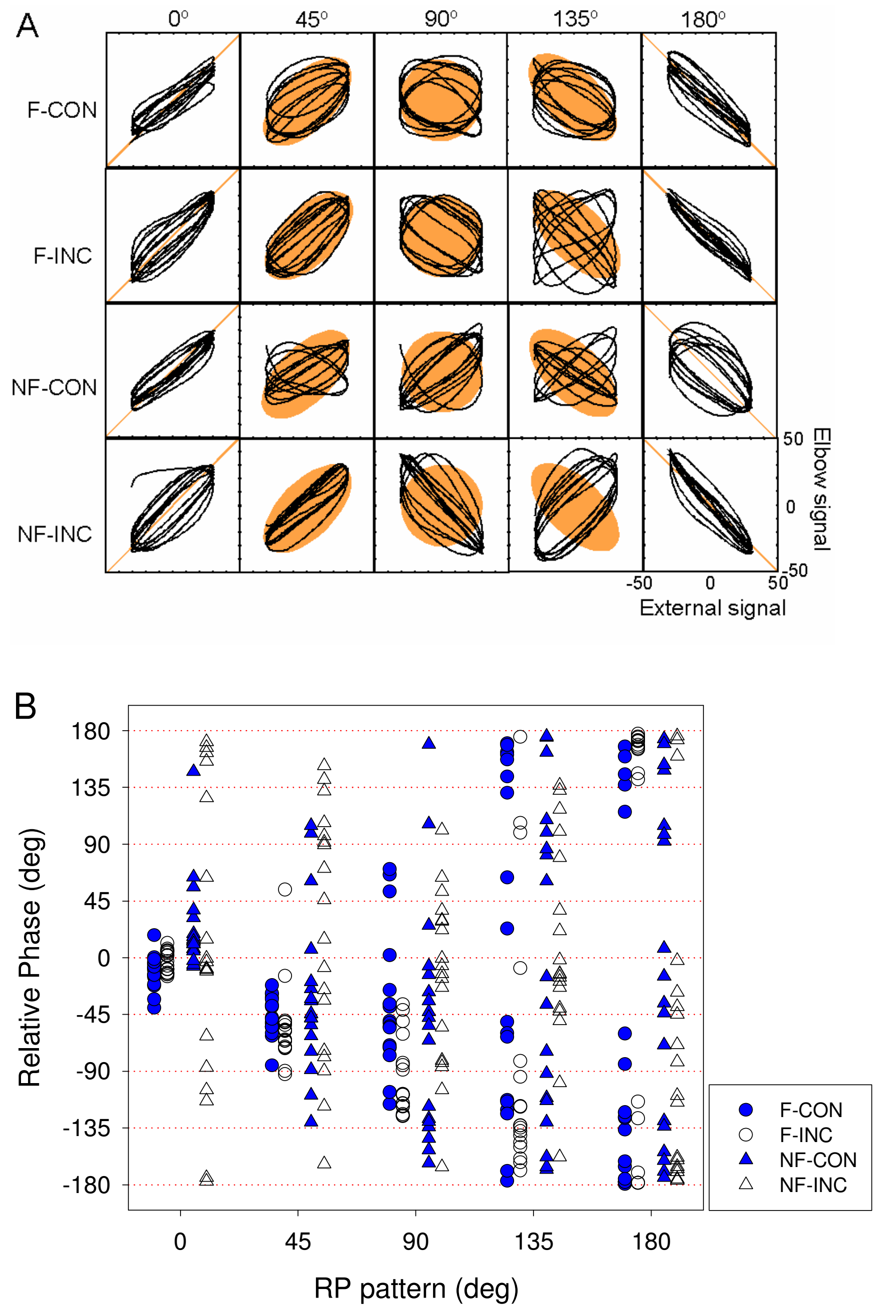

Fig 3. (A) Example angle-angle plots and **(B)** all individual trial mean RP values from the pre-practice scanning trials. **(A)** The 45° lines represent the required 0° and 180° RP patterns, the shaded circles the required 90° RP pattern, and the shaded ellipses the required 45° and 135° RP patterns. Row 1 (F-CON) and row 3 (NF-CON) are from the same congruent participant, and row 2 (F-INC) and row 4 (NF-INC) are from the same incongruent participant.

congruency groups, the 45°, 90°, and 135° relative phase patterns were not associated with any clustering (Fig 3B). Table 1 represents the number of trials with relative phase values within the ±22.5° band around the required relative phase value. For example, the number of observations for the 90° relative phase pattern represents the number of trials with a mean relative phase value between -67.5° to -112.5°. Across the 5 scanned relative phases, significantly more trials were found within the ±22.5° band in the feedback condition (60.6%) compared to the no feedback condition (28.3%) ($\chi^2_{(1)} = 37.84$, $p < .01$) (Table 1). However, the 2 Congruency × 2 Band chi-square test failed to detect any statistical difference between congruency groups ($p > .05$).

Table 1. Number of observed trials within ±22.5° of the required RP values as a function of feedback-congruency from the pre-practice scanning trials in the Experiment 1 (total 18 trials).

	0°	45°	90°	135°	180°
F-CON	16	16	5	4	9
F-INC	18	11	7	9	14
NF-CON	13	9	0	2	5
NF-INC	6	2	4	0	10

Absolute phase error and *phase variability*

A significant main effect of Pattern was found in the ϕ_{AE} data, ($F_{(4, 40)} = 4.49$, $p < .01$) (Fig 4A). Post-hoc tests revealed that the ϕ_{AE} values were significantly smaller in the 0°, 45°, and 180° relative phase patterns compared to the 90° and 135° relative phase patterns,

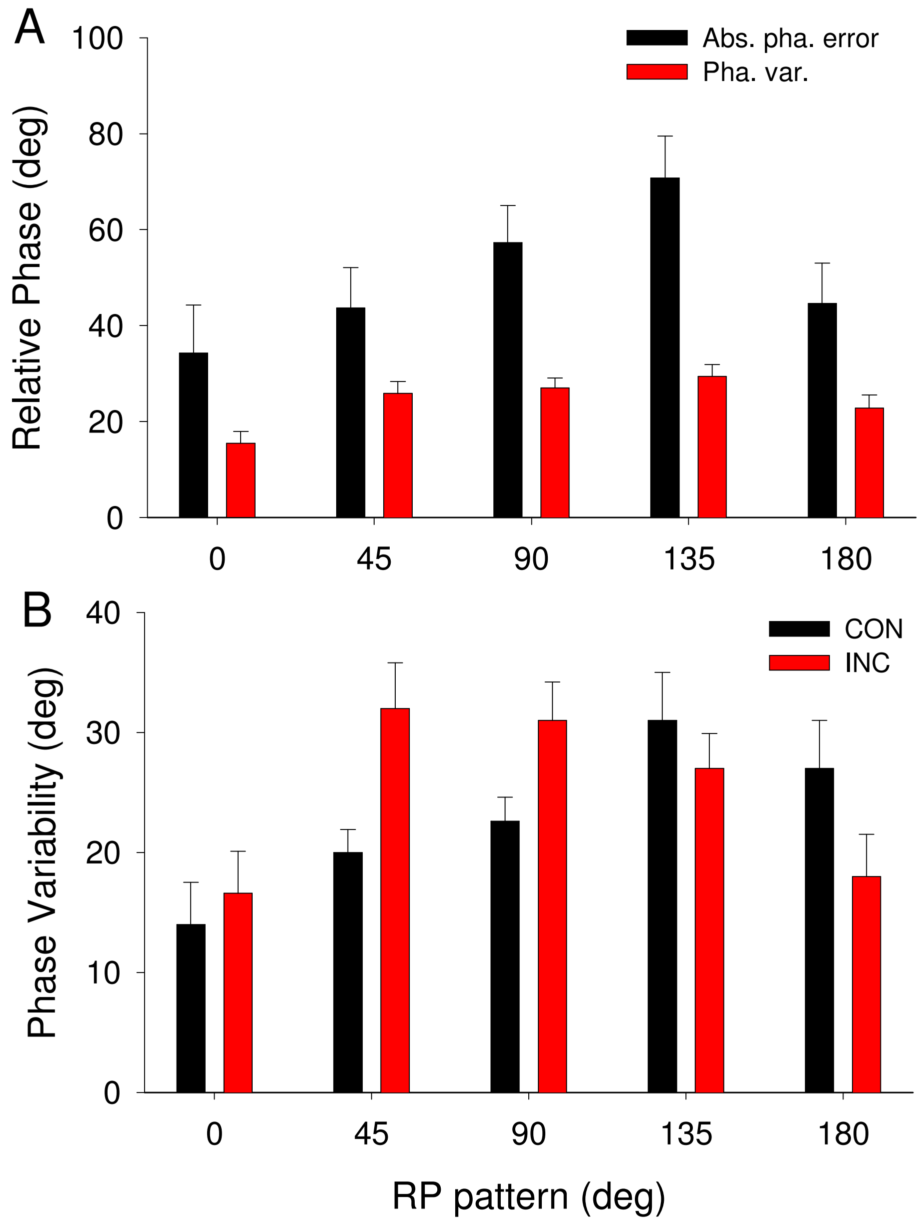

Fig 4. Group means of absolute phase error (ϕ_{AE}) and phase variability (ϕ_{SD}) from the pre-practice scanning session. **(A)** Absolute phase error and phase variability are plotted as a function of required target pattern. **(B)** Phase variability is plotted as a function of congruency and required target pattern. The error bars represent standard error of between subject variability.

with the largest ϕ_{AE} in the 135° relative phase pattern. The no feedback condition (ϕ_{AE} = 70.7°) was characterized by significantly larger ϕ_{AE} than the feedback condition (ϕ_{AE} = 29.6°), ($F_{(1, 10)} = 14.4$, $p < .01$). The analysis of the ϕ_{AE} data revealed a significant Congruency × Feedback effect, ($F_{(1, 10)} = 5.21$, $p < .05$). Simple main effect tests revealed two main findings. First, the incongruent group (ϕ_{AE} = 86.8°) was significantly less accurate than the congruent group (ϕ_{AE} = 22.5°) when tracking without visual feedback. Second, the incongruent group had significantly larger ϕ_{AE} in the no feedback condition (ϕ_{AE} = 86.8°) compared to the feedback condition (ϕ_{AE} = 54.6°).

A significant main effect of Pattern was found in the ϕ_{SD} data, ($F_{(4, 40)} = 6.37$, $p < .01$), and post-hoc tests revealed that the 0° relative phase pattern was the most stable pattern among the five relative phase patterns (Fig 4A). A significant main effect of Feedback, ($F_{(1, 10)} = 6.3$, $p < .05$), revealed that performance in the no feedback condition (ϕ_{SD} = 27.7°) was more variable than the feedback condition (ϕ_{SD} = 20.5°). The analysis of the ϕ_{SD} data also revealed a significant Congruency × Pattern interaction effect, ($F_{(4, 40)}$ = 4.11, $p < .01$) (Fig 4B). Simple main effect tests revealed two important findings. First, within the incongruent group the 0° and 180° relative phase patterns were the most stable and within the congruent group the 0° and 45° relative phase patterns were the most stable. Second, the congruent group's performance was significantly less variable at 45° and 90° relative phases and more variable at 180° relative phase compared to the incongruent group.

Joint amplitude and amplitude variability

The analysis of the joint amplitude revealed no significant main effects or interactions. Mean joint amplitude across groups was 63.7° (std = 12.1°). A significant main effect of Feedback was found in the amplitude variability data, ($F_{(1, 10)} = 5.54$, $p < .05$), revealing that the amplitudes produced in the no feedback condition (mn = 4.33°) were more variable than the feedback condition (mn = 3.68°).

Tracking frequency

No significant main effects or interactions were found in the tracing frequency data. Mean tracing frequency was 0.82 Hz (std = 0.06 Hz).

Practice

Example trials of visuomotor tracking performance from early (Fig. 5A, B, C) and late (Fig. 5D, E, F) in practice have been plotted in Figure 5. Individuals were unable to produce the 90° relative phase pattern at the start of Day 1, yet could produce the 90° relative phase pattern by the end of Day 2 with an improvement in relative phase and phase variability towards the 90° relative phase.

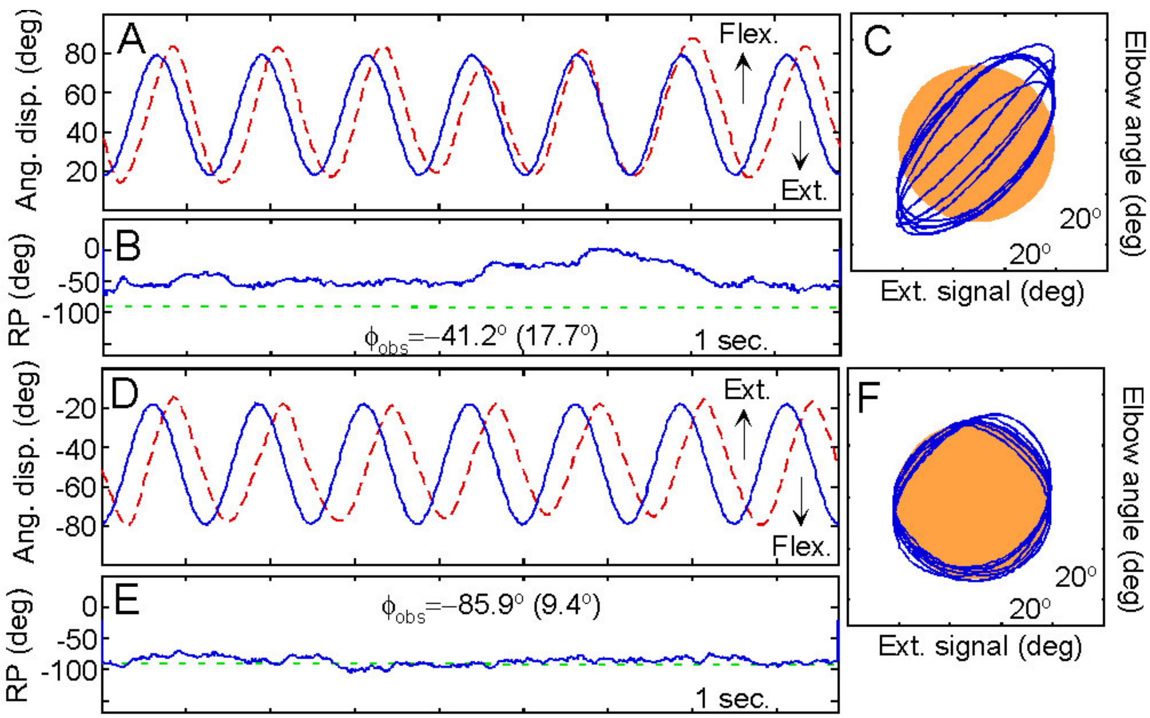

Fig 5. The external signal and the elbow angle time series **(A, D)** and the corresponding continuous relative phase trace **(B, E)** and angle-angle plots **(C, F)** are shown. **A, B,** and **C** represent an example trial produced by a congruent participant early in practice (day 1 block 1). **D, E,** and **F** represent an example trial produced by an incongruent participant late in practice (day 2 block 6).

Absolute phase error and phase variability

Practice produced a shift in the observed relative phase as revealed by a significant reduction in ϕ_{AE} from Day 1 (ϕ_{AE} = 14°) to Day 2 (ϕ_{AE} = 10°), ($F_{(1, 10)}$ = 14.14, $p < .01$), and a significant shift in ϕ_{AE} from practice Block 1 (ϕ_{AE} = 14°) to Block 6 (ϕ_{AE} = 10°), ($F_{(5, 50)}$ = 3.32, $p < .05$).

The analysis of the ϕ_{SD} data revealed that the shift toward the required relative phase goal of 90° was accompanied by a significant decrease in visuomotor tracking variability from Day 1 (ϕ_{SD} = 16°) to Day 2 (ϕ_{SD} = 12°), ($F_{(1, 10)}$ = 40.06, $p < .01$), and a significant reduction from practice Block 1 (ϕ_{SD} = 15.6°) to Block 6 (ϕ_{SD} = 13.2°), ($F_{(5, 50)}$ = 3.12, $p < .05$).

Joint amplitude and amplitude variability

The analysis of the joint amplitude data revealed no significant main effects or interactions. Mean joint amplitude across groups was 60.9° (std = 3.38°). With practice, variability in elbow amplitude decreased significantly from day 1 (mn = 3.3°) to day 2 (mn = 2.6°), ($F_{(1, 10)}$ = 34.57, $p < .01$).

Tracking frequency

Mean tracking frequency was 0.82 Hz (std = 0.02), meaning that participants paced close to the required tracking frequency value of 0.8 Hz. The incongruent group (mn = 0.83 Hz) had a significantly faster tracking frequency than the congruent group (mn = 0.8 Hz), ($F_{(1, 10)} = 7.12$, $p < .05$).

Test of practice effect: pre-practice scanning vs. post-practice scanning

General characteristics of relative phase patterns in post-practice scanning

A comparison of Figure 6A to Figure 3A suggests that practice with the required 90° pattern influenced the tracking performance of all 5 visuomotor tracking patterns in both feedback conditions and for both congruency groups. Figure 6B shows that in the feedback condition, behavior was generally clustered at the required relative phase values for all relative phase patterns for both congruency groups. In the no feedback condition, behavior was less clustered for the 90°, 135°, and 180° relative phase patterns in comparison to the feedback condition for both congruency groups (Fig 6B). However, performance of the 0° and 45° relative phase patterns without feedback were more consistent for the congruent group compared to the incongruent group.

Overall, more trials were found within the ±22.5° range for all relative phase patterns in the feedback condition (78.9%) compared to the no feedback condition

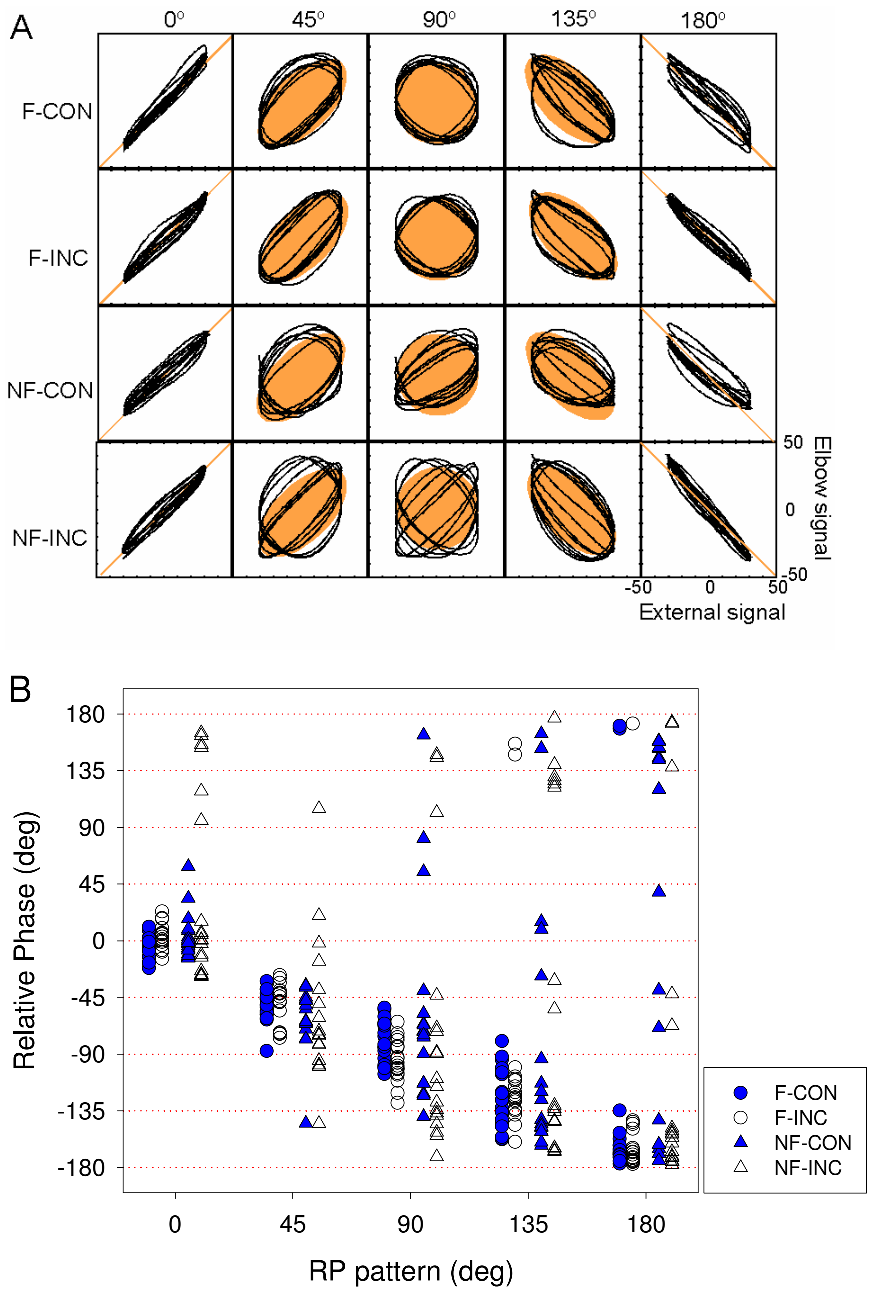

Fig 6. (A) Example angle-angle plots and **(B)** all individual trial mean RP values from the post-practice scanning trials. **(A)** Row 1 (F-CON) and row 3 (NF-CON) are produced by the same congruent participant as shown in Fig. 3A row 1 and row 3. Row 2 (F-INC) and row 4 (NF-INC) are produced by the same incongruent participant as shown in Fig. 3A row 2 and row 4.

(48.3%) in the post-practice scanning session as well ($\chi^2_{(1)} = 36.3$, $p < .01$) (Table 2). More trials fell within the ±22.5° range in the congruent group (71.1%) compared to the incongruent group (56.1%) ($\chi^2_{(1)} = 8.75$, $p < .01$) (Table 2). Additionally, a 2 Session (pre-practice, post-practice) × 2 Band chi-square test was performed in order to examine changes in the number of observations within the ±22.5° range following practice. The test revealed that the number of observed trials within the bin increased with practice (pre-practice : 44.4%, post-practice : 63.6%) ($\chi^2_{(1)} = 26.6$, $p < .01$) (compare Table 1 and 2).

Table 2. Number of observed trials within ±22.5° of the required RP values as a function of feedback-congruency from the post-practice scanning trials in the Experiment 1 (total 18 trials).

	0°	45°	90°	135°	180°
F-CON	18	17	12	11	15
F-INC	17	12	15	11	14
NF-CON	16	14	6	10	9
NF-INC	8	3	5	6	10

Absolute phase error and phase variability

Each relative phase pattern was analyzed separately in a 2 Congruency × 2 Feedback × 2 Session (pre-practice scanning, post-practice scanning) ANOVA. The results for each pattern will be presented in the following order: (1) 90° relative phase pattern as the practiced pattern, (2) 0° and 180° relative phase patterns together, and (3) 45° and 135° relative phase patterns together.

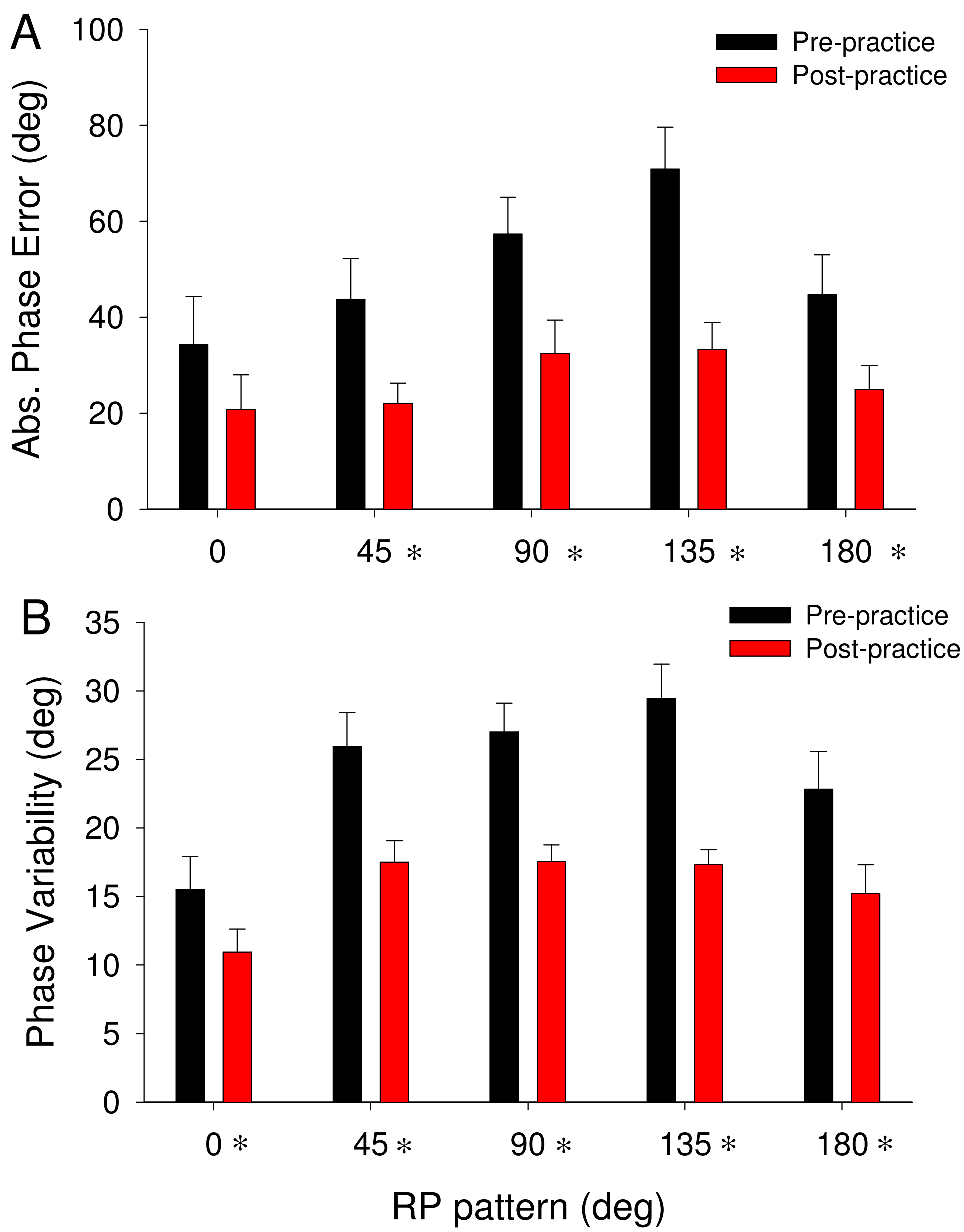

Fig 7. Group means of absolute phase error (ϕ_{AE}) and phase variability (ϕ_{SD}). **(A)** Absolute phase errors are plotted as a function of required target pattern and scanning session. **(B)** Phase variability is plotted as a function of required target pattern and scanning session. The error bars represent standard error of between subject variability. Asterisk signs represent statistical significance.

The analysis of the ϕ_{AE} data from the 90° relative phase pattern revealed a significant main effect of Session, ($F_{(1, 10)} = 7.38$, $p < .05$), suggesting that practice of the required 90° relative phase pattern led to a decrement in phase error (Fig 7A). A significant main effect of Feedback was also found in the ϕ_{AE} data, ($F_{(1, 10)} = 8.47$, $p < .05$), with the no feedback condition ($\phi_{AE} = 61.2°$) resulting in larger phase error than the feedback condition ($\phi_{AE} = 28.6°$). The analysis of the ϕ_{SD} data from the 90° relative phase condition revealed a significant main effect of Session, ($F_{(1, 10)} = 35.41$, $p < .01$), revealing that the required 90° relative phase training condition was produced with significantly less variability following 2 days practice (Fig 7B). The analysis of the ϕ_{SD} data from the 90° relative phase pattern also revealed significant main effects of Feedback, ($F_{(1, 10)} = 29.46$, $p < .01$) and Congruency, ($F_{(1, 10)} = 7.4$, $p < .05$). These results show that the 90° relative phase pattern was produced with less variability with feedback ($\phi_{SD} = 17.2°$) compared to without feedback ($\phi_{SD} = 27.3°$). The congruent group ($\phi_{SD} = 20°$) produced less variable tracking performance with the 90° pattern compared to the incongruent group ($\phi_{SD} = 24.5°$). A significant interaction of Congruency × Session was found in the ϕ_{SD} data in the 90° relative phase pattern, ($F_{(1, 10)} = 6.9$, $p < .05$). Simple main effect tests revealed that the congruent group ($\phi_{SD} = 22.7°$) was less variable than the incongruent group ($\phi_{SD} = 31.4°$) in the pre-practice session. In the post-practice session, there was no difference between the groups.

The analysis of the ϕ_{AE} data from revealed a significant main effect of Session for the 180° relative phase pattern, ($F_{(1, 10)} = 8.93$, $p < .05$), but not for the 0° relative phase pattern ($p > .05$) (Fig 7A). Significant main effects of Feedback were found in both the 0°

and 180° relative phase patterns in the ϕ_{AE} data, ($Fs_{(1, 10)} > 5.82$, $ps < .05$), with the no feedback condition (0°: ϕ_{AE} = 46°, 180°: ϕ_{AE} = 49.3°) characterized by larger phase error than the feedback condition (0°: ϕ_{AE} = 9.1°, 180°: ϕ_{AE} = 21.2°). A marginal main effect of Congruency in the 0° relative phase pattern, ($F_{(1, 10)} = 4.91$, $p = .05$), revealed that the congruent group (ϕ_{AE} = 14.6°) had less ϕ_{AE} than the incongruent group (ϕ_{AE} = 40.5°). A significant Congruency × Feedback interaction was found in the 0° relative phase pattern, ($F_{(1, 10)} = 5.54$, $p < .05$). Simple main effect tests revealed no statistical difference between congruency groups in the feedback condition. However, the incongruent group (ϕ_{AE} = 72.9°) had significantly larger ϕ_{AE} than the congruent group (ϕ_{AE} = 19.1°) in the no feedback condition. The analysis of the ϕ_{SD} data revealed significant main effects of Session for both the 0° and 180° relative phase patterns, ($Fs_{(1, 10)} > 5.28$, $ps < .05$), with performance of the 0° and 180° relative phase patterns less variable in the post-practice scanning trials (Fig 7B).

The analysis of the ϕ_{AE} data from the 45° and 135° relative phase conditions revealed significant main effects of Session, ($Fs_{(1, 10)} > 18.54$, $ps < .05$), with smaller ϕ_{AE} for both patterns in the post-practice scanning trials (Fig 7A). Significant main effects of Feedback were found in both the 45° and 135° relative phase patterns in the ϕ_{AE} data, ($Fs_{(1, 10)} > 21.25$, $ps < .01$), with the no feedback condition (45°: ϕ_{AE} = 50.6°, 135°: ϕ_{AE} = 67.9°) associated with larger ϕ_{AE} than the feedback condition (45°: ϕ_{AE} = 15.3°, 135°: ϕ_{AE} = 36.2°). A significant main effect of Congruency was found in the 45° relative phase pattern, ($F_{(1, 10)} = 8.8$, $p < .05$), with the congruent group (ϕ_{AE} = 21°) characterized by smaller ϕ_{AE} than the incongruent group (ϕ_{AE} = 44.8°). Significant interactions of

Congruency × Feedback were found in both the 45° and 135° relative phase patterns, ($Fs_{(1, 10)} > 4.98$, $ps < .05$). For the 45° relative phase pattern, the simple main effect tests revealed that while there was no statistical difference between congruency groups in the feedback condition, the incongruent group (ϕ_{AE} = 69.1°) had significantly larger ϕ_{AE} than the congruent group (ϕ_{AE} = 32.1°) in the no feedback condition. For the 135° relative phase pattern, the simple main effect tests revealed that the incongruent group (ϕ_{AE} = 78.1°) had significantly larger ϕ_{AE} than the congruent group (ϕ_{AE} = 57.6°) in the no feedback condition. A significant Feedback × Session interaction was found in the 45° relative phase pattern, ($F_{(1, 10)} = 5.95$, $p < .05$). Simple main effect tests revealed that the values of ϕ_{AE} were less in the feedback condition (pre-practice: ϕ_{AE} = 18.4°, post-practice: ϕ_{AE} = 12.1°) than in the no feedback condition (pre-practice: ϕ_{AE} = 69.1°, post-practice: ϕ_{AE} = 32.1°) in both scanning sessions. The post-practice session (ϕ_{AE} = 32.1°) also had significantly smaller values of ϕ_{AE} than the pre-practice session (ϕ_{AE} = 69.1°) in the no feedback condition.

The analysis of the ϕ_{SD} data revealed significant main effects of Session for both the 45° and 135° relative phase conditions, ($Fs_{(1, 10)} > 17.34$, $ps < .01$), with smaller ϕ_{SD} values in the post-practice scanning trials for both coordination patterns (Fig 7B). A significant main effect of Congruency in the 45° relative phase pattern revealed that the congruent group (ϕ_{SD} = 17.8°) was less variable than the incongruent group (ϕ_{SD} = 25.6°), ($F_{(1, 10)} = 7.48$, $p < .05$). A significant main effect of Feedback was found in the 45° relative phase pattern, ($F_{(1, 10)} = 14.38$, $p < .01$), revealing that the feedback condition (ϕ_{SD} = 17.1°) was less variable than the no feedback condition (ϕ_{SD} = 26.3°). A significant interaction of Congruency × Session was found in the 45° relative phase pattern, ($F_{(1, 10)} = 5.26$, $p < .05$). Simple main effect tests revealed that the congruent group ($\phi_{SD} = 19.8°$) was less variable than the incongruent group ($\phi_{SD} = 32.1°$) in the pre-practice session, and that the post-practice session (CON: $\phi_{SD} = 15.9°$, INC: $\phi_{SD} = 19.2°$) was less variable than the pre-practice session (CON: $\phi_{SD} = 19.8°$, INC: $\phi_{SD} = 32.1°$) in both congruency groups.

Joint amplitude and amplitude variability

The analysis of joint amplitude data found a significant main effect of Feedback in the 0° relative phase pattern, ($F_{(1, 10)} = 8.17$, $p < .05$), revealing that the angular amplitude was significantly larger in the no feedback condition (mn = 68.1°) than in the feedback condition (mn = 59.9°).

The analysis of the amplitude variability data found significant main effects of Session in all relative phase patterns except the 0° relative phase pattern, $Fs(1, 10) = 7.8$, $p < .05$, revealing that the amplitude variability was significantly reduced with practice in the post-practice scanning trials (Fig 8). A significant interaction of Congruency × Session was found in the 90° relative phase pattern, ($F_{(1, 10)} = 6.14$, $p < .05$). Simple main effect tests revealed that the angular amplitude was less variable in the post-practice session (CON: mn = 2.9°, INC: mn = 2.3°) than the pre-practice scanning session (CON: mn = 3.7°, INC: mn = 4.4°) in both congruency groups. However, no statistical difference between congruency groups across sessions was found. A significant interaction of Feedback × Session was found in the 180° relative phase pattern, ($F_{(1, 10)}$ =

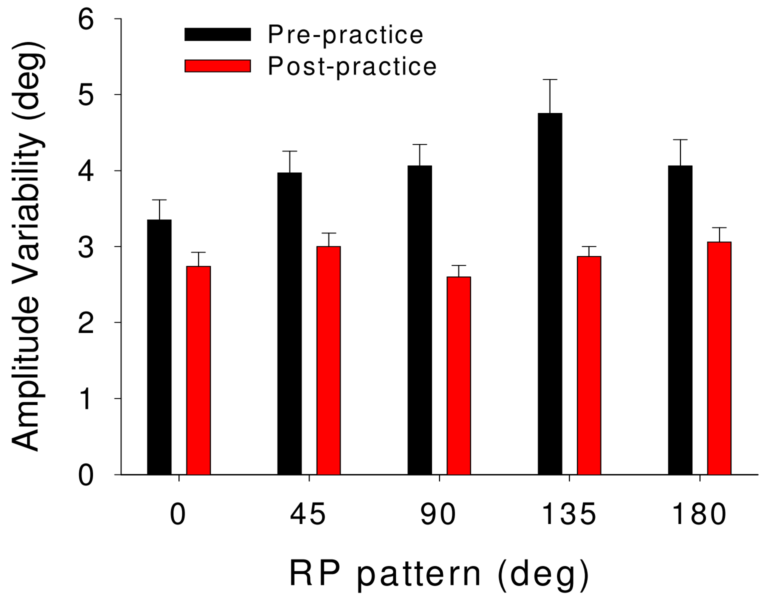

Fig 8. Amplitude variability is plotted as a function of required target pattern and scanning session. The error bars represent standard error of between subject variability.

13.2, $p < .01$). Simple main effect tests revealed that the amplitude variability was less in the post-practice session (mn = 2.9°) compared to the pre-practice session (mn = 4.7°) when tracking with visual feedback.

Tracking frequency

A significant main effect of Feedback was found in the 0° relative phase pattern, ($F_{(1, 10)}$ = 5.59, $p < .05$), revealing that the no feedback condition (mn = 0.81 Hz) was characterized by a faster movement frequency than the feedback condition (mn = 0.78 Hz). A significant main effect of Congruency was found in the 135° relative phase pattern, ($F_{(1, 10)} = 6.31$, $p < .05$), revealing that the incongruent group (mn = 0.84 Hz) had a faster movement frequency than the congruent group (mn = 0.8 Hz). A significant interaction of Feedback × Session was found in the 180° relative phase pattern, ($F_{(1, 10)} = 17.39$, $p < .01$). Simple main effect tests revealed an overall faster movement frequency in the no feedback condition (mn = 0.85 Hz) compared to the feedback condition (mn = 0.82 Hz) in the pre-practice session, and vice versa in the post-practice session (F: mn = 0.84 Hz, NF: mn = 0.8 Hz). Faster movement frequencies were found in the pre-practice session (mn = 0.85 Hz) compared to the post-practice session (mn = 0.8 Hz) when tracking with no feedback.

Discussion

Prior to practice of the 90° relative phase tracking pattern, the 0° and 45° relative phase patterns were generally more accurate and more stable compared to the other relative phase patterns in the congruent group. Interestingly, the 0° relative phase pattern was the most stable pattern in both congruency groups, whereas the incongruent group produced a more accurate and less variable 180° relative phase pattern compared to the congruent group. A unique finding was that the incongruent group's performance of the 0° relative phase pattern when tracking without visual feedback was less accurate. This shows the importance of visual feedback for the incongruent group in increasing the strength of perception-action coupling. Overall performance was coarse based on phase accuracy and stability when tracking without feedback for both congruent and incongruent groups. The loss of feedback for the incongruent group had a more detrimental impact on phase accuracy compared to the congruent group.

Practice of the required 90° relative phase pattern led to a decrease in phase error and a shift toward the required relative phase goal of 90°. Moreover, the required 90° relative phase pattern became more stable with practice. This suggests that practicing the required 90° relative phase pattern resulted in the establishment of a new attractor state at 90° in both congruency groups (Zanone & Kelso, 1992, 1997; Lee et al., 1995; Kelso & Zanone, 2002; Buchanan, 2004). Thus, practicing the same visually defined structure led to learning of the same 90° relative phase pattern regardless of visuomotor congruency. Joint amplitude production also became less variable with practice.

With extensive practice of the 90° relative phase pattern, overall improvements in phase accuracy were observed across all relative phase patterns except the 0° relative phase pattern, with an increase in the stability of all the scanned patterns. The above findings suggest that practicing the required 90° relative phase visuomotor tracking pattern led to a general transfer of visuomotor tracking skills to the non-practiced patterns. Accompanied with the overall improvements of relative phase performance, general improvements in amplitude production also were observed across all relative phase patterns except the 0° relative phase pattern.

Again, practice results showed that both congruency groups learned the required relative phase pattern of 90° with equal pattern accuracy and stability during the practice sessions. This finding was contrary to pervious visuomotor tracking studies showing that a congruent visuomotor mapping enhanced the learning processes compared to an incongruent visuomotor mapping or delayed feedback (Carnahan et al., 1996; Grafton et al., 2001). One plausible explanation for this finding was that the overlapping of the two signals in the same workspace benefited the incongruent group in learning the required phase relationship between the external signal and the limb's motion. With the overlapping display performers possibly utilized the distance between the slope of the external signal and the slope of the limb's feedback. The benefit of the overlapping display might make comparison and integration easier between the external signal and the limb's signal because of the decrease in visual search cost (Wickens and Carswell, 1995). Work by Wickens and Carswell (1995) suggest that spatial proximity, which refers to spatial closeness in presenting information, can improve perceptual motor performance. Many tracking studies have also demonstrated that visuomotor performance was influenced by spatial proximity between informational signals (Bailey, 1958; Chernikoff & LeMay, 1963; Sampson & Elkin, 1965; Fracker & Wickens, 1989; Wickens & Andre, 1990; Wickens & Carswell, 1995; Reed et al., 2003). For instance, Reed et al. (2003) required participants to track a horizontally moving signal (dot) with a joystick in five separate conditions. The external signal was always presented at the middle level of a screen, while the joystick cursor was positioned at the external signal level, 4.5 cm (3.2° retinal eccentricity of participant's eyes) above and below, and 9.0 cm (6.4°) above and below. Results showed that tracking performance was the most accurate when both signals were at the same level, and that an increased separation of the signals reduced accuracy significantly.

A question arises here also as to whether or not the spatial proximity between two signals affected the control and learning of a coordination pattern based on visuomotor congruency. In Experiment 2, participants performed the same tracking task as in Experiment 1 but in a dual window workspace. The external signal and the limb's feedback were presented in different windows in the same workspace. The idea behind the display mode was that the integrated display mode used in Experiment 1 provided overlapping signals to easily compare the relationship between the external signal and the performer's feedback; in turn, visuomotor incongruence was not detrimental to learning (Wickens & Carswell, 1995). However, a dual window produces a separation in signals which may lead to a detrimental effect in the incongruent feedback condition. The relationship between congruency and workspace integrity was examined in Experiment 2.

CHAPTER IV

EXPERIMENT 2

Methods

Subjects

A total of twelve undergraduate and graduate students (6 males and 6 females, mean age = 23.4) volunteered to participate in the study. The experimental protocol and consent form were approved by the IRB board of Texas A&M University and all participants signed a consent form prior to the experiment. All participants are self-reported right handers and had normal or corrected-to-normal vision. Each participant was randomly assigned to an experimental group (6 participants per group) based on visuomotor congruency as defined in Experiment 1.

Apparatus

The apparatus was the same as in Experiment 1

Task and procedures

The task and procedures were identical to those used in Experiment 1 except the display of the signals on the computer monitor was altered. Participants were presented with the external sinusoidal signal and the online visual feedback in 2 different workspaces. The workspaces were 14 cm (length) × 4.5 cm (height), and vertically 0.5 cm apart from each other. The top workspace was for the external signal and presented 2 peak-to-peak cycles of the external signal during a trial. The participant's limb motion was displayed in the lower window.

Data analysis

All data analyses were the same as in Experiment 1.

Results

Pre-practice scanning

General characteristics of relative phase patterns

Example trials from the pre-practice scanning session are shown as a function of feedback-congruency in Figure 9A. In the feedback condition, the 0° and 180° patterns were produced consistently, whereas the 45°, 90°, and 135° patterns were characterized by some attraction towards the 0° and 180° relative phase patterns (Fig 9A). The removal of visual feedback had an impact on the production of all 5 relative phase patterns (Fig 9A). Inspection of Figure 9B shows that the most clustering (circles)

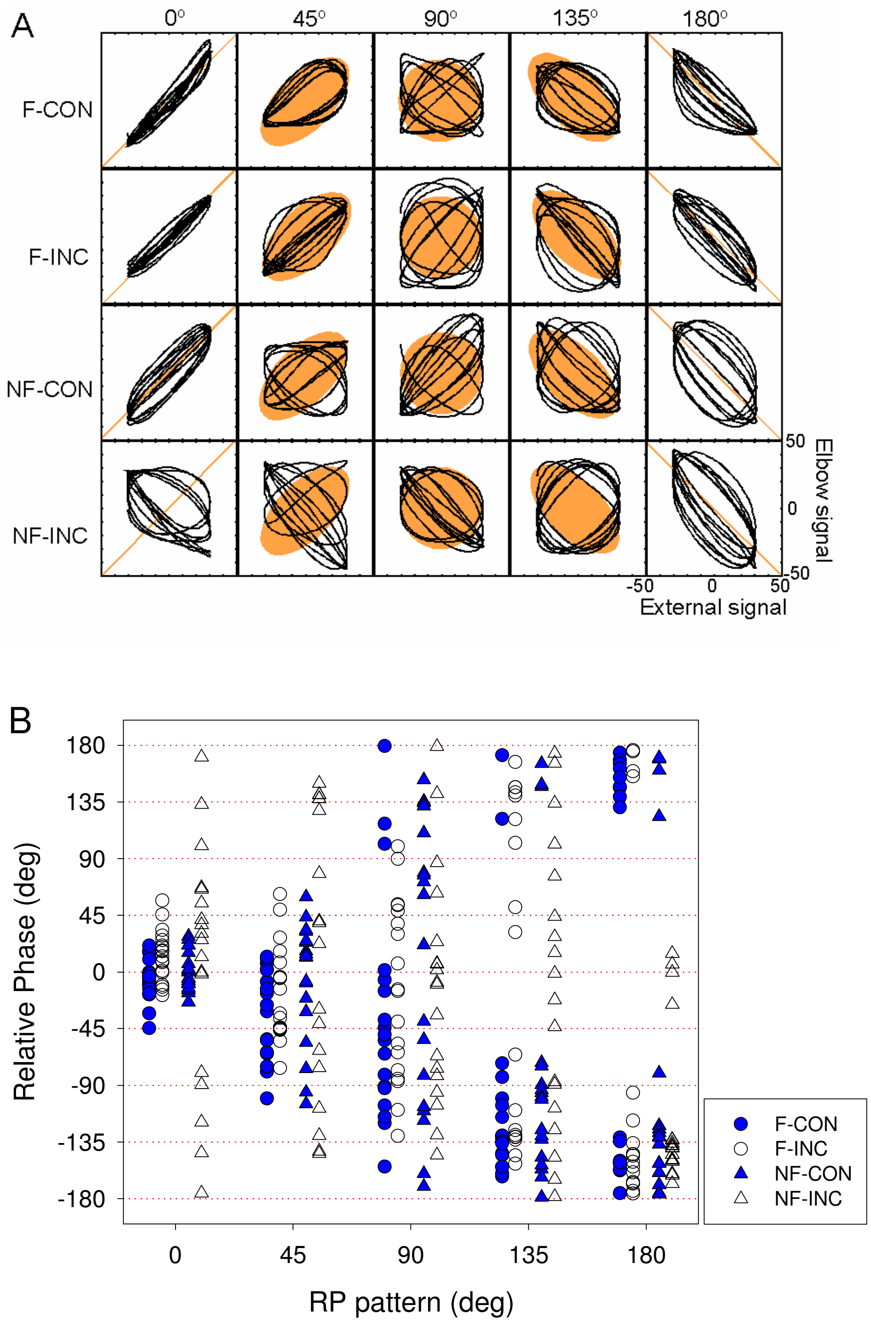

Fig 9. (A) Example angle-angle plots and **(B)** all individual trial mean RP values from the pre-practice scanning trials. **(A)** The 45° lines represent the required 0° and 180° RP patterns, the shaded circles the required 90° RP pattern, and the shaded ellipses the required 45° and 135° RP patterns. Row 1 (F-CON) and row 3 (NF-CON) are from the same congruent participant, and row 2 (F-INC) and row 4 (NF-INC) are from the same incongruent participant.

occurred at the 0° and 180° relative phase patterns in the feedback condition, meaning that individuals could produce the required 0° and 180° relative phase patterns relatively well without any practice in both congruency groups. In the no feedback condition, the most clustering (closed triangles) emerge for the 0° relative phase pattern in the congruent group (Fig 9B). Overall, more trials were found within the ±22.5° range in the feedback condition (46.1%) compared to the no feedback condition (27.2%) in the pre-practice scanning trials ($\chi^2_{(1)} = 13.8$, $p < .01$) (Table 3). More observations within the ±22.5° range were found in the congruent group (42.2%) compared to the incongruent group as well (31.1%) ($\chi^2_{(1)} = 4.78$, $p < .05$) (Table 3).

Table 3. Number of observed trials within ±22.5° of the required RP values as a function of feedback-congruency from the pre-practice scanning trials in the Experiment 2 (total 18 trials).

	0°	45°	90°	135°	180°
F-CON	16	6	4	10	6
F-INC	13	8	4	7	9
NF-CON	15	2	3	6	8
NF-INC	3	3	4	2	3

Absolute phase error and phase variability

A significant main effect of Pattern was found in the ϕ_{AE} data, ($F_{(4, 40)} = 7.64$, $p < .01$) and post-hoc tests revealed that the 0° and 180° relative phase patterns were produced with the smallest error and that the 90° relative phase pattern was produced with the largest error (Fig 10). The no feedback condition (ϕ_{AE} = 63.5°) was characterized by larger ϕ_{AE} than the feedback condition (ϕ_{AE} = 37.7°), ($F_{(1, 10)}$ = 16.16, p < .01). A significant main effect of Congruency revealed that the congruent group (ϕ_{AE} = 39.3°) had smaller ϕ_{AE} values than the incongruent group (ϕ_{AE} = 61.9°), ($F_{(1, 10)}$ = 16.16, p < .01). The analysis of the ϕ_{SD} data found a significant main effect of Pattern, ($F_{(4, 40)}$ = 12.47, p < .01), and post-hoc tests revealed that the 0° relative phase pattern was the least variable pattern, and that the 90° and 135° relative phase patterns were the most variable patterns (Fig 10).

Joint amplitude and amplitude variability

The analysis of the joint amplitude data revealed no significant main effects or interactions. Mean joint amplitude across the groups was 59.6° (std = 10.6°). A significant main effect of Pattern was found in amplitude variability data, ($F_{(4, 40)}$ = 5.68, p < .01). Post-hoc tests revealed that amplitude production was less variable for the 0° (mn = 3.02°) and 45° (mn = 3.37°) relative phase patterns compared to the other relative phase patterns (mn = 4.02°).

Tracking frequency

No significant main effects or interactions were found in the tracing frequency data. Mean tracing frequency was 0.8 Hz (std = 0.04 Hz).

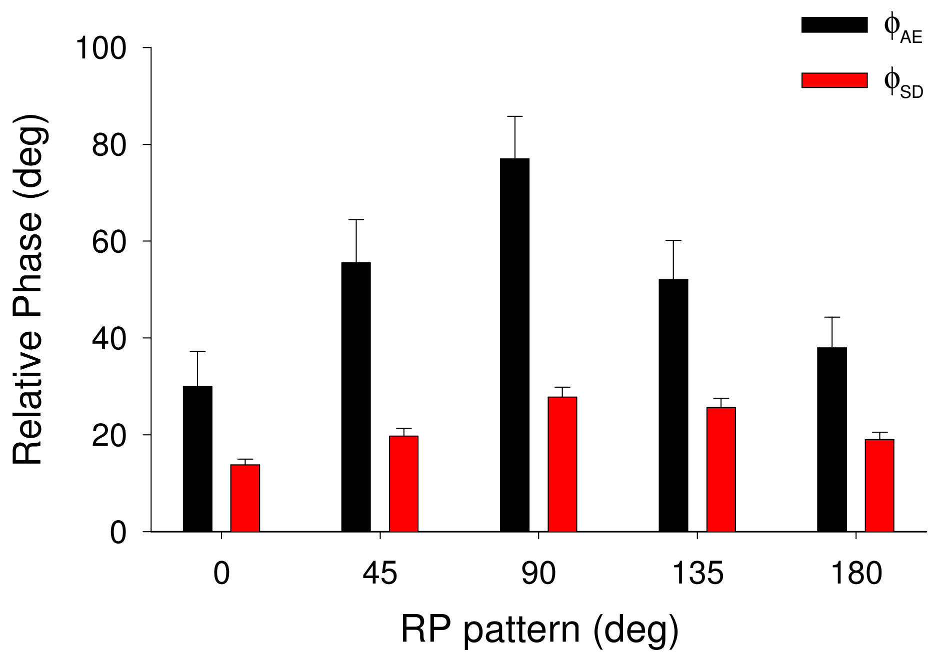

Fig 10. Group means of absolute phase error (ϕ_{AE}) and phase variability (ϕ_{SD}) from the pre-practice scanning session. The error bars represent standard error of between subject variability.

Practice

Representative practice trials for the separate display mode are shown in Figure 11A (congruent) and 11B (incongruent). Individuals were unable to produce the 90° relative phase pattern with accuracy and consistency at the start of Day 1 (Fig 11A), yet could produce the 90° relative phase pattern by the end of Day 2 (Fig 11B).

Absolute phase error and phase variability

The congruent group (ϕ_{AE} = 17.8°) was characterized by smaller ϕ_{AE} values compared to the incongruent group (ϕ_{AE} = 23.7°), ($F_{(1, 10)} = 5.04$, $p < .05$). Practice resulted in a significant reduction in the observed ϕ_{AE} values from Day 1 (ϕ_{AE} = 26°) to Day 2 (ϕ_{AE} = 15.5°), ($F_{(1, 10)} = 23.85$, $p < .01$).

The analysis of the ϕ_{SD} data revealed that the shift toward the required relative phase goal of 90° was accompanied by a significant decrease in performance variability from Day 1 (ϕ_{SD} = 22.7°) to Day 2 (ϕ_{SD} = 20.1°), ($F_{(1, 10)} = 40.06$, $p < .01$). A significant Day × Block interaction was found, ($F_{(5, 50)} = 3.59$, $p < .01$). Simple main effect tests revealed a significant reduction in ϕ_{SD} from practice Blocks 1 through 5 to Block 6 in Day 1, with no difference across blocks in Day 2 (Fig 12A). The ϕ_{SD} values from Block 1 to Block 5 were significantly larger in Day 1 compared to those of Day 2 (Fig 12A).

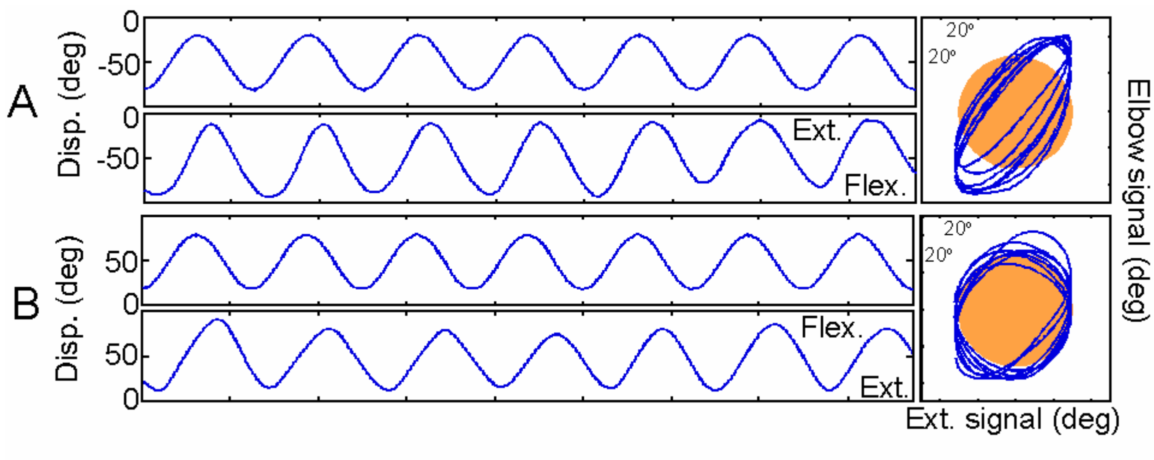

Fig 11. The external signal and the elbow angle time series and their corresponding angle-angle plots are shown. **A)** An example trial produced with incongruent feedback early in practice (day 1 block 1). **B)** An example trial produced with congruent feedback late in practice (day 2 block 6).

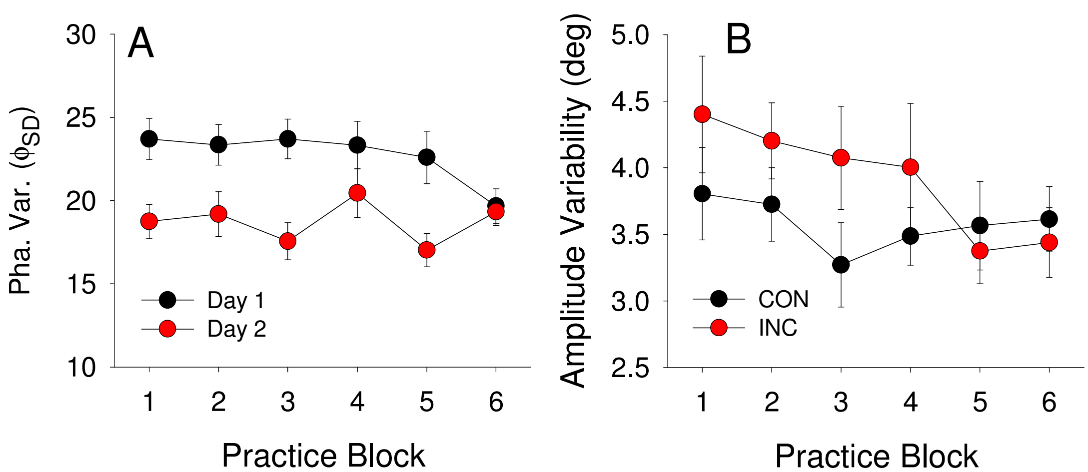

Fig 12. Group means of phase variability (ϕ_{SD}) and amplitude variability from the practice session. **(A)** Phase variability is plotted as a function of day and practice block. **(B)** Joint amplitude variability is plotted as a function of congruency and practice block. The error bars represent standard error of between subject variability.

Joint amplitude and amplitude variability

The congruent group (mn = 61°) produced a significantly smaller elbow joint motion compared to the incongruent group (mn = 65°), ($F_{(1, 10)} = 4.99$, $p < .05$). A significant main effect of Block was found, ($F_{(5, 50)} = 2.86$, $p < .05$). Post-hoc tests revealed that the joint amplitudes from Block 4 and 6 were significantly larger than those of the other four blocks (mn of Block 4 and 6 = 64.6°, mn of Block 1, 2, 3, and 5 = 62.2°).

With practice, amplitude variability significantly decreased across blocks, ($F_{(5, 50)} = 3.48$, $p < .01$). Post-hoc tests revealed that the variability values from Block 1 and 2 were significantly larger than those of Blocks 3 – 6 (mn of Block 1 and 2 = 4.1°, mn of Block 3 - 6 = 3.6°). A significant interaction of Congruency × Block was found, ($F_{(5, 50)} = 2.51$, $p < .05$). Simple main effect tests revealed that the congruent group produced significantly less variable joint amplitudes in Block 1 through Block 4 compared to the incongruent group. Block 3 and 4 were characterized by less variable joint amplitudes compared to the other Blocks in the congruent group, while the amplitude variability decreased with increasing Block number in the incongruent group (Fig 12B).

Tracking frequency

Mean tracking frequency was 0.8 Hz (std = 0.02). No main effects or interactions were found.

Test of practice effect: pre-practice scanning vs. post-practice scanning

General characteristics of relative phase patterns in post-practice scanning

A comparison of Figure 12A to Figure 9A suggests a performance change for all 5 visuomotor tracking patterns in both feedback conditions and both congruency conditions. Inspection of Figure 13B shows an increase in clustering at the required relative phase values, especially for the 0° and 180° relative phase patterns in the feedback condition. In the no feedback condition, there was a larger scatter in the mean values for both congruency groups (Fig 13B). Overall, more observations within the ±22.5° range were found in the feedback condition (64.4%) compared to the no feedback condition (41.7%) ($\chi^2_{(1)} = 18.74$, $p < .01$) (Table 4). However, there was no significant difference in the number of trials within the ±22.5° range as a function of congruency groups ($p = 0.24$). A 2 Session $\times$ 2 Band chi-square test revealed that the number of trials within the ±22.5° range increased from the pre-practice (36.7%) to the post-practice session (53.1%) ($\chi^2_{(1)} = 19.5$, $p < .01$) (compare Table 3 and 4).

Absolute phase error and phase variability

As done in Experiment 1, each relative phase pattern was analyzed separately in a 2 Congruency $\times$ 2 Feedback $\times$ 2 Session ANOVA in order to compare the phase performance between pre-scanning and post-scanning practice sessions. The results for

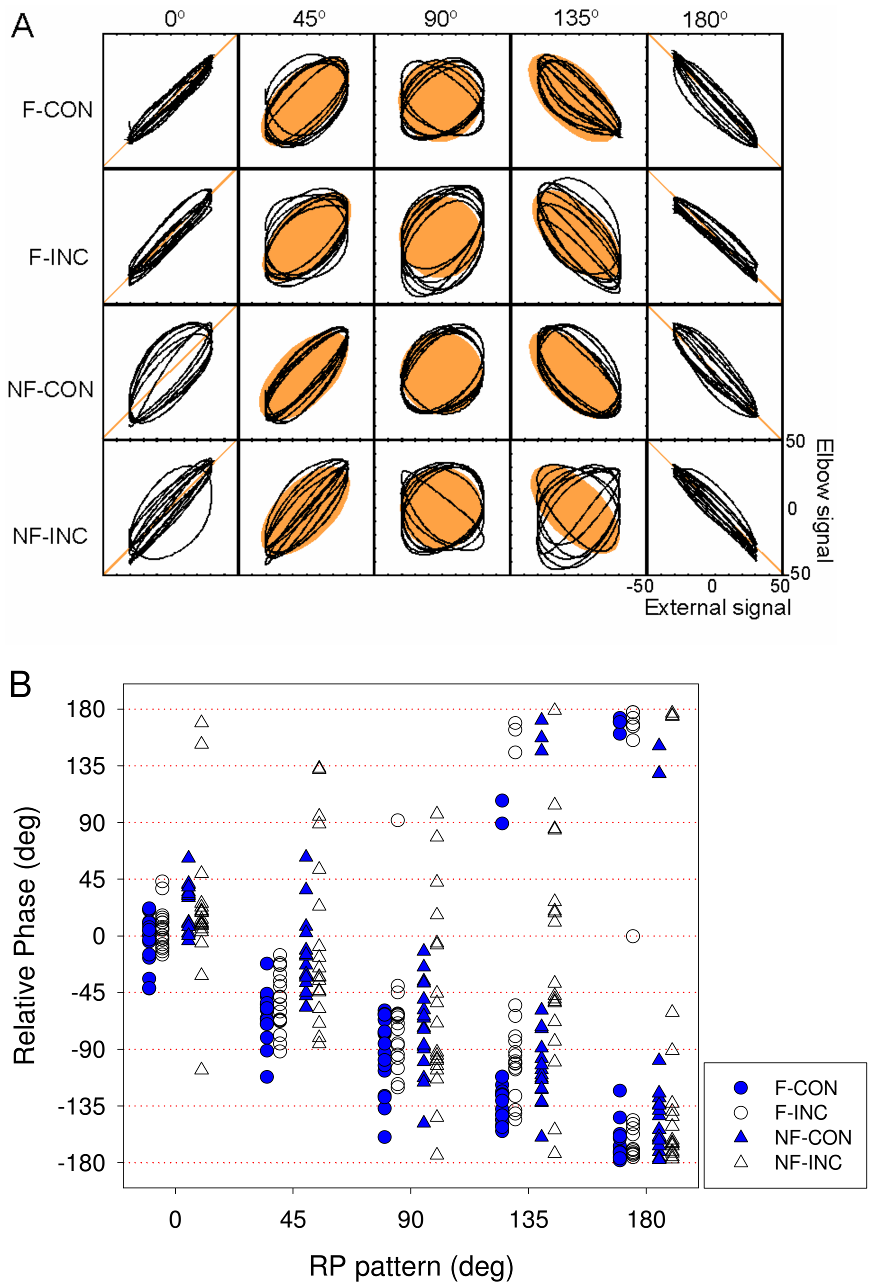

Fig 13. (A) Example angle-angle plots and **(B)** all individual trial mean RP values from the post-practice scanning trials. **(A)** Row 1 (F-CON) and row 3 (NF-CON) were produced by the same congruent participant as shown in Fig. 9A row 1 and row 3. Row 2 (F-INC) and row 4 (NF-INC) were produced by the same incongruent participant as shown in Fig. 9A row 2 and row 4.

Table 4. Number of observed trials within ±22.5° of the required RP values as a function of feedback-congruency from the post-practice scanning trials in the Experiment 2 (total 18 trials).

	0°	45°	90°	135°	180°
F-CON	15	11	9	14	15
F-INC	16	12	7	4	13
NF-CON	9	9	6	6	7
NF-INC	11	7	7	1	12

each pattern will be presented in the following order: (1) 90° relative phase pattern as the practiced pattern, (2) 0° and 180° relative phase patterns together, and (3) 45° and 135° relative phase patterns together.

The analysis of the ϕ_{AE} data from the 90° relative phase condition found a significant main effect of Session, ($F_{(1, 10)} = 18.77$, $p < .01$), revealing that practice of the required 90° relative phase pattern led to a decrease in phase error (Fig 14A). The analysis of the ϕ_{SD} data from the 90° relative phase condition found a significant main effect of Session, ($F_{(1, 10)} = 5.19$, $p < .05$), showing that the required 90° relative phase training pattern was performed with less variability following practice (Fig 14C).

Main effects of Session were not found in the 0° and 180° relative phase conditions, ($ps > .05$) (Fig 14A). Significant main effects of Feedback were found in both the 0° and 180° relative phase patterns in the ϕ_{AE} data, ($Fs_{(1, 10)} > 6.46$, $ps < .05$), revealing that the no feedback condition (0°: $\phi_{AE} = 36.9°$, 180°: $\phi_{AE} = 39.6°$) was characterized by larger ϕ_{AE} values than the feedback condition (0°: $\phi_{AE} = 14.9°$, 180°: $\phi_{AE} = 22.8°$). A significant Congruency × Session interaction was found in the ϕ_{AE} data from the 0° relative phase condition, ($F_{(1, 10)} = 9.92$, $p < .05$). Post-hoc tests revealed that the

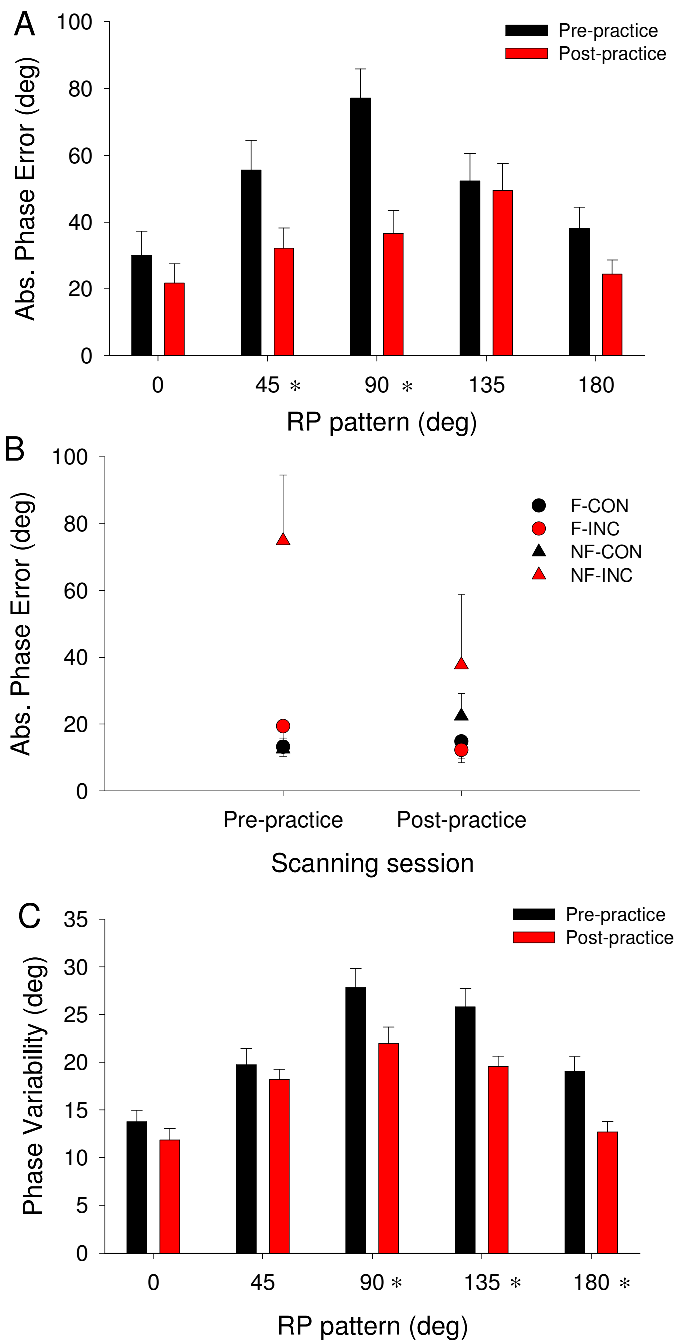

Fig 14. Group means of absolute phase error (ϕ_{AE}) and phase variability (ϕ_{SD}). **(A)** Absolute phase errors are plotted as a function of required target pattern and scanning session. **(B)** Absolute phase errors in the 0° RP pattern are plotted as a function of feedback and congruency. **(C)** Phase variability is plotted as a function of required target pattern and scanning session. The error bars represent standard error of between subject variability. Asterisk signs represent statistical significance.

incongruent group's ϕ_{AE} decreased from the pre-practice (ϕ_{AE} = 47.1°) to the post-practice scanning session (ϕ_{AE} = 25°). A significant 3 way interaction of Feedback × Congruency × Session was found in the ϕ_{AE} data from the 0° relative phase condition, ($F_{(1, 10)}$ = 5.11, p < .05) (Fig 14B). The incongruent group's ϕ_{AE} values decreased from pre-practice to post-practice scanning in the no feedback condition. A significant main effect of Congruency in the 0° relative phase pattern revealed that the congruent group (mn = 10.4°) produced smaller ϕ_{SD} than the incongruent group (ϕ_{SD} = 15.2°), ($F_{(1, 10)}$ = 12.94, p < .01). The analysis of the ϕ_{SD} data from the 180° relative phase pattern condition revealed a significant main effect of Session, ($F_{(1, 10)}$ = 8.62, p < .05), with smaller ϕ_{SD} in the post-practice scanning trials (Fig 14C).

A significant main effect of Session was found in the 45° relative phase pattern, ($F_{(1, 10)}$ = 12.78, p < .01), with smaller ϕ_{AE} in the post-practice scanning trials (Fig 14A). A significant main effect of Feedback in the 45° relative phase pattern revealed that the no feedback condition (ϕ_{AE} = 60.7°) produced larger ϕ_{AE} than the feedback condition (ϕ_{AE} = 27°), ($F_{(1, 10)}$ = 8.26, p < .05). A significant main effect of Congruency was found in the 135° relative phase pattern, ($F_{(1, 10)}$ = 19.78, p < .01), with the congruent group (ϕ_{AE} = 31.6°) characterized by smaller ϕ_{AE} values than the incongruent group (ϕ_{AE} = 70.2°). The analysis of the ϕ_{SD} data revealed a significant main effect of Session in the 135° relative phase pattern, ($F_{(1, 10)}$ = 7.71, p < .05) , with smaller ϕ_{SD} in the post-practice scanning trials (Fig 14C). A significant main effect of Congruency in the 45° relative phase pattern revealed that the congruent group (ϕ_{SD} = 16.5°) was less variable than the incongruent group (ϕ_{SD} = 21.4°) ($F_{(1, 10)}$ = 5.58, p < .05). A significant Feedback × Congruency interaction was found in the 45° relative phase pattern, ($F_{(1, 10)} > 5.43$, $p < .05$). Simple main effect tests revealed that the incongruent group's visuomotor tracking (ϕ_{SD} = 24.5°) was more variable than the congruent group (ϕ_{SD} = 15.4°) in the no feedback condition, and that the incongruent group was more variable without feedback (ϕ_{SD} = 24.5°) than with feedback (ϕ_{SD} = 18.4°).

Joint amplitude and amplitude variability

The analysis of joint amplitude data found significant main effects of Session in the 0°, 45°, and 135° relative phase patterns, ($Fs_{(1, 10)} > 6.26$, $ps < .05$), revealing that the angular amplitude significantly increased with practice (Fig 15A). The analysis of amplitude variability data found significant main effects of Session in the 90°, and 135° relative phase patterns, ($Fs_{(1, 10)} > 7.4$, $ps < .05$), revealing that the amplitude variability was significantly reduced in the post-practice scanning session for these relative phase patterns (Fig 15B). A significant main effect of Feedback was found in the 135° relative phase pattern, ($F_{(1, 10)} = 7.64$, $p < .05$), revealing that joint amplitude in the no feedback condition (mn = 3.38°) was less variable than in the feedback condition (mn = 3.9°).

Tracking frequency

A significant main effect of Congruency was found in the 180° relative phase pattern, ($F_{(1, 10)} = 7.56$, $p < .05$), revealing that the congruent group (mn = 0.82 Hz) had faster

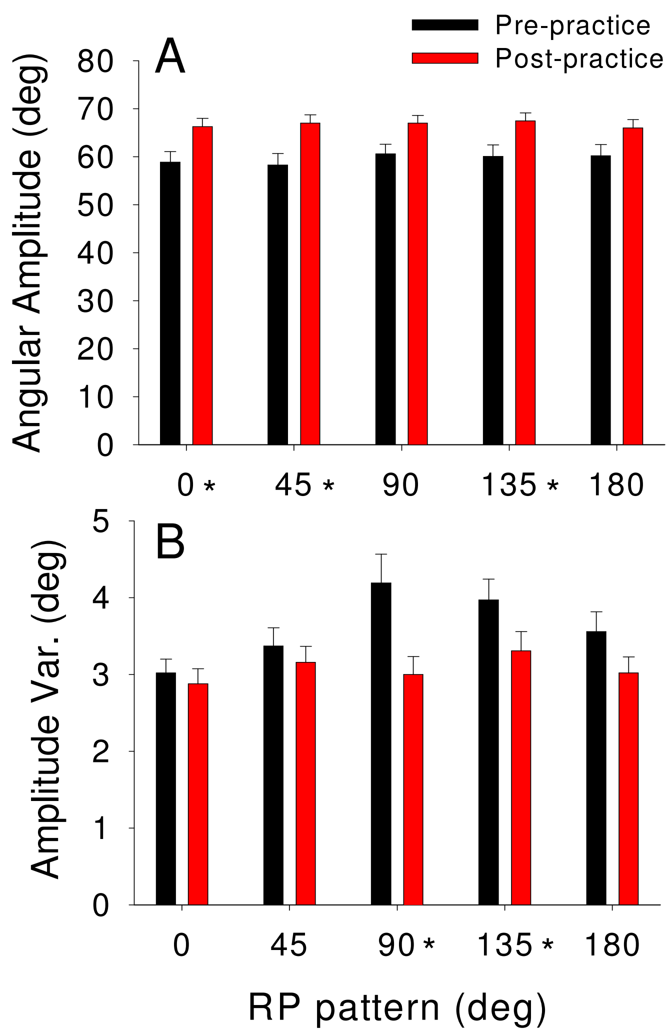

Fig 15. (A) Joint amplitude and **(B)** amplitude variability are plotted as a function of required target pattern and scanning session. The error bars represent standard error of between subject variability. Asterisk signs represent statistical significance.

movement frequency than the incongruent group (mn = 0.79 Hz). A significant interaction of Feedback × Congruency was found in the 45° relative phase pattern, ($F_{(1, 10)} = 4.45$, $p < .05$). Simple main effect tests revealed that the congruent group (0.81 Hz) had faster movement frequency than the incongruent group (mn = 0.78 Hz) in the no feedback condition. In the incongruent group, faster movement frequencies were found in the feedback condition (mn = 0.81 Hz) compared to the no feedback condition (mn = 0.78 Hz).

Comparisons between workspace modes

In order to examine the effect of workspace modes (Experiment 1 vs. Experiment 2), a 2 Workspace (same, separate) × 2 Congruency ANOVA was conducted for the 0°, 90°, and 180° relative phase patterns in the feedback condition. The 0° and 180° relative phase patterns were chosen as intrinsic coordination patterns, and the 90° relative pattern was chosen as the practice pattern. The analysis of the ϕ_{AE} and ϕ_{SD} data from the 0° and 180° patterns revealed no significant main effects or interactions. In the comparison of 90° relative phase pattern between workspaces, a significant main effect of Workspace was found in the ϕ_{SD} data, ($F_{(1, 20)} = 15.13$, $p < .01$), confirming that the same workspace ($\phi_{SD} = 12.6°$) produced more stable pattern visuomotor tracking than the separate workspace ($\phi_{SD} = 21.4°$).

Discussion

Phase accuracy results of the pre-practice scanning session suggest that the 0°and 180° relative phase patterns were more accurate than the other patterns in the feedback condition. The 0° relative phase pattern was the most stable pattern among the relative phase patterns and the 90° and 135° relative phase patterns were the least stable patterns. Overall phase accuracy was reduced when tracking without feedback. Consistent with the finding of Experiment 1, the phase accuracy of the 0° relative phase pattern was impacted more in the incongruent group when visual feedback was removed.

Practice of the required relative phase pattern of 90° led to a significant decrease in phase error and pattern variability, suggesting the establishment of a new attractor state at 90°. Amplitude stability was also improved with practice. Contrary to the findings of the practice session in Experiment 1, visuomotor congruency effects were found in the dual window workspace. The congruent group produced more accurate visuomotor tracking and less variable elbow amplitude compared to the incongruent group. The above findings suggest that the dual workspace window influenced the incongruent group by providing a weak perceptual workspace, consistent with the basic assumption of display proximity proposed in the Introduction.

Overall improvements in phase accuracy were observed in the 45° and 90° relative phase pattern. An increase in performance stability at the 90°, 135°, and 180° relative phases was found. The above findings suggest that practicing the required 90°

relative phase visuomotor tracking pattern led to a general transfer of visuomotor tracking skills to non-practiced patterns. A reduction in joint amplitude variability was found in the 90°, and 135° relative phase patterns.

The comparisons between the same workspace (in Experiment 1) and the separate workspace (Experiment 2) demonstrated that providing different signals together in the same workspace (Experiment 1) enhanced pattern stability in the formation of perceptually defined patterns compared to providing signals in the separate workspace (Experiment 2). The enhancement from the same workspace was found in the 90° relative phase pattern which was the least stable pattern, compared to the intrinsically stable 0° and 180° relative phase patterns. The present finding suggests that spatial proximity in presenting information plays an important role in learning of a novel visuomotor tracking pattern compared to the intrinsically stable tracking patterns (e.g., 0°, 180°). This observation might be associated with visual search patterns (Roerdink et al., 2005). That is, participants with separate workspace might ignore their feedback to compare the external signal during the 0° and 180° relative phase tracking patterns, while the participants tried to search and compare the two signals for performing the required 90° relative phase pattern.

CHAPTER V

GENERAL DISCUSSION

Learning of a 90° relative phase visuomotor tracking pattern: interaction of workspace and visuomotor congruency

One of the main purposes of the present study was to investigate how visuomotor congruency influenced the learning of a specific relative phase tracking pattern. The dynamic pattern theory in the realm of motor skill learning predicts that learning will take the form of a phase transition from an unstable pattern to a stable pattern (Schöner et al., 1992). This transition occurs when the to-be-learned environmentally specified pattern does not coincide with a preexisting stable attractor in the system's coordination landscape (Schöner et al., 1992; Zanone & Kelso, 1992, 1997; Kelso & Zanone, 2002). The present study showed that both congruency groups learned the required relative phase pattern with a significant decrease in relative phase error when tracking the external signal with a 90° relative phase pattern. The decrease in relative phase error was accompanied by a significant decrease in relative phase variability. These findings were consistent with previous bimanual research in that learning a relative phase pattern, which was not part of the systems intrinsic dynamics, emerged as a phase transition, whereby a repeller was transformed into an attractor with practice (Schöner et al., 1992; Zanone & Kelso, 1992, 1997; Fountaine et al., 1997; Kelso & Zanone, 2002). Thus, the two congruency groups demonstrated proof of learning with no difference in pattern stability by the end of practice. This implies that visuomotor congruency (mapping) between a limb's motion and its visual feedback might not be a dominant factor to learn a specific visuomotor pattern. Instead, the perceptual structure between two visual components may predominant over visuomotor congruency in determining the characteristic learning phenomena in the present study.

The incongruent group exhibited worse phase accuracy in the separate workspace while no differences were found in the same workspace. Moreover, amplitude accuracy and variability were worse in the incongruent group than the congruent group when tracking in the separate workspace condition, whereas no such congruency effect was found in the same workspace condition. These results demonstrate that visuomotor congruency and workspace mode have some level of interaction in the present visuomotor tracking tasks. Why did visuomotor congruency only affect learning in the separate display mode? With the signals in the same workspace, participants may be able to more easily compare the relationship between the signals. Since the incongruency in the present experiment did not convert to 90° relative phase pattern to a more stable pattern, such as 180° to 0° pattern with incongruent feedback (Bogaerts et al., 2003; Roerdink et al., 2005), the same window provided a perceptual display that was stronger than the distortion between vision and proprioceptive feedback produced by the incongruency effect. The separate workspace, on the other hand, was hard to search and compare both signals, which impacted negatively on the incongruent group's coupling strength between motor production and its feedback (Bailey, 1958; Chernikoff & LeMay, 1963; Sampson & Elkin, 1965;

Fracker & Wickens, 1989; Wickens & Andre, 1990; Wickens & Carswell, 1995; Reed et al., 2003). In the present study, the separate workspace drew out the weaker perception-action coupling in the incongruent condition, whereas the same workspace could compensate for the incongruent information.

A unique finding in the comparison between the workspaces was that the workspace manipulation seemed to affect pattern stability much more for the to-be-learned 90° relative phase pattern compared to the intrinsically stable, 0° or 180° relative phase patterns. Why did the workspace differences impact the stability differentially between the stable patterns and the to-be-learned 90° relative phase pattern? Wickens and Carswell (1995) suggested that the spatial proximity between objects (signals) will impact task performance. Presenting signals close together in space makes signal comparison and integration easier due to the decrease in visual search cost and time to go from one signal to the other. Based on this search cost idea, the search cost for the intrinsically stable patterns was less even within the separate workspace, whereas the search cost for the to-be-learned pattern increased with the separate workspace and the same workspace effectively reduced the cost. This search cost might influence the strength of perception-action coupling in the present study. Byblow et al. (1995) found that visuomotor tracking with a continuous display of the to-be-tracked signals produced less phase variability than with a discrete display. The authors suggested that the continuous information served to compress variability by increasing the perceptual threshold for information resolution in the tracking task. Taken together, spatial proximity in the workspace played a role in determining the strength of perception-action coupling by changing the perceptual threshold associated with search cost, in turn, influencing the learning of a new visuomotor tracking pattern in the present study.

Evolution of attractor landscape with practice: practice stabilizes entire visuomotor tracking system

The other purpose of the present study was to examine the influence of learning a new visuomotor tracking pattern on the system's intrinsic dynamics. The results of the scanning sessions in the present study showed several notable findings resulting from extended practice of the required 90° relative phase tracking pattern. First, generally all measured relative phase patterns became more accurate and more stable following the extended practice of the 90° relative phase visuomotor tracking pattern, especially in Experiment 1. The Zanone and Kelso (1992) bimanual learning study found that learning the novel 90° relative phase pattern led to a significant loss of stability in the 180° relative phase pattern. The authors argued that initially the less stable 180° pattern lost stability as the strength of the memory for the 90° relative phase pattern increased. However, this finding has not been consistently replicated in other learning studies, reporting that acquisition of a new relative phase pattern stabilizes unpracticed relative phase patterns such as 0° and 180° relative phase patterns (Buchanan, 2004; Fontaine et al., 1997). The present study was consistent with the last studies since stabilization of the 90° relative phase pattern increased the stability of the other relative phase patterns.

Since a unilateral visuomotor tracking task eliminates the interaction between two effectors, the differential stability across relative phase patterns in the present study might have emerged from a resolution of the perception-action system's perceptual thresholds (Schmidt et al., 1990; Wimmers et al., 1992; Byblow et al., 1995). Thus, the overall accuracy and stability improvements at all relative phase patterns may be associated with an overall improvement in the resolution ability of the whole perception-action system to track an external signal.

Second, practicing the 90° relative phase pattern did not make a stronger attractor state than the other non-practiced relative phase patterns based on the observations of Figures 7B and 14C. These findings were contrary to previous bimanual learning studies, demonstrating that practicing a new relative phase pattern made a 'valley' at the practiced relative phase in the attractor landscape (Zanone & Kelso, 1992, 1997; Kelso & Zanone, 2002), with the practiced relative phase pattern stabilized much more than other nearby relative phase patterns. Although the present study demonstrated that practicing the to-be-learned pattern stabilized the practiced 90° relative phase pattern as well as the other relative phase patterns, the practiced 90° relative phase pattern was not associated with a stronger attraction compared to the other nearby 45° and 135° patterns after practice. One possible explanation may be that the length of practice was not long enough to develop a stronger attractor state at the practiced 90° relative phase compared to the other non-practiced relative phase patterns. This explanation might be rejected, since the other non-practiced relative phase patterns were stabilized following practice of the 90° relative phase pattern. Wimmers et al.

(1992, see also Schmidt et al., 1990) suggested that such differential stability in a visuomotor tracking task might be explained by the coupling strength of the environment-actor system which functions by virtue of perceptual thresholds constraining the ability to synchronize with the external event. That is, the ability to resolve information about differences in signals leads to differences in stability among patterns. The spatiotemporal quality of a visuomotor task will be dependent on the strength of the coupling between perceptual processes and action processes, with coupling strength decreasing as a perceptual threshold is reached (Schmidt et al., 1990; Wimmers et al., 1992; Buekers et al., 2000). Based on the above ideas, the general landscape of the visuomotor tracking system would be similar to the initial system's landscape, with overall improvements of the other non-practiced relative phase patterns.

Impact of feedback and visuomotor congruency on pattern accuracy and stability

The pre-practice scanning data demonstrated that generally the 0° relative phase pattern was more accurate than the other relative phase patterns in the feedback condition regardless of congruency groups (Wilson et al., 2005). According to the perceptual threshold idea (Schmidt et al., 1990; Wimmers et al., 1992; Byblow et al., 1995), the 0° relative phase tracking pattern required the least perceptual processing to resolve information about differences in the two signals. When tracking without visual feedback, however, the incongruent group produced worse phase accuracy compared to the congruent group. This finding suggests the importance of visual feedback for tracking accuracy in motor control (Ceux et al., 2003). More importantly, the performers were dependant more on visual information about the two signals than on motoric (proprioceptive) information between the external signal and the elbow motion in the present task (Mechsner et al., 2001). Grafton et al. (2001) also demonstrated that in a sequence learning task with visuomotor tracking, learning with an incongruent visuomotor mapping occurred at the perceptual level and not at the motor level.

The present study showed that performance of the 0° relative phase pattern (also the 45° relative phase pattern in Experiment 1) was influenced more than the other relative phase patterns when tracking without feedback. The incongruent group required an anti-phase tracking between an external signal and a limb's motion in order to produce the visually defined 0° relative phase pattern when tracking without visual feedback. Previous research has shown that in-phase tracking was more stable and more accurate than anti-phase tracking when tracking without visual feedback of a limb's motion (Wimmers et al., 1992; Peper & Beek, 1998; Buekers et al., 2000; Ceux et al. 2003). However, the anti-phase tracking pattern became as stable and accurate as the in-phase tracking pattern when providing transformed visual feedback in order to produce a perceived in-phase pattern (Bogaerts et al., 2003; Roerdink et al., 2005). In the present study, the findings that the incongruent group had better phase accuracy on the 0° relative phase pattern with feedback than without feedback supports the conclusion that transformed visual feedback can increase the strength of perception-action coupling.

In terms of pattern stability, the feedback condition was less variable than the no feedback condition, demonstrating the powerful role of visual feedback in pattern stabilization (Ceux et al., 2003). In Experiment 1, phase variability results demonstrated that in both feedback conditions the 0° (also 45° relative phase pattern) relative phase pattern was generally more stable compared to the other relative phase patterns in the congruent group, while the 0° and 180° relative phase patterns were more stable than the other patterns in the incongruent group. These findings are important in elucidating the interaction between visuomotor congruency and feedback. The 0° relative phase pattern was more stable than the other patterns with congruent feedback, consistent with previous research (Wimmers et al., 1992; Peper & Beek, 1998; Buekers et al., 2000; Ceux et al. 2003). In the incongruent group, the transformed feedback stabilized the 0° relative phase pattern which was actually an anti-phase tracking between a limb's motion and an external signal. This result from the feedback condition supports previous studies showing that transformed visual feedback to a mirrored image (a perceived in-phase pattern) between two oscillators enhanced stability of anti-phase pattern tracking (Bogaerts et al., 2003; Roerdink et al., 2005). Second, it was also notable that the 180° relative phase pattern was as stable as the 0° relative phase pattern in the incongruent group, but not in the congruent group. As already stated, anti-phase tracking was less stable than in-phase tracking without visual feedback (Wimmers et al., 1992; Peper & Beek, 1998; Buekers et al., 2000; Ceux et al. 2003). From this fact, it was not surprising that the congruent group was less stable in the 180° relative phase pattern than in the 0° relative phase pattern regardless of feedback condition. However, the results of the incongruent group clearly imply that the incongruent group utilized an in-phase tracking between an external signal and a limb's motion in order to produce the perceived 180° relative phase pattern regardless of visual feedback. Even if the incongruent group used two visual signals to produce the 180° relative phase pattern in the feedback condition, the in-phase coupling between the external signal and the limb's motion helped the perceptually less stable 180° relative phase pattern stabilize in some way. This finding was consistent with previous research showing that transformed visual feedback did not impact the stability of an in-phase pattern (Bogaerts et al., 2003; Roerdink et al., 2005).

CHAPTER VI

CONCLUSIONS

The present experiments demonstrated the importance of perception-action coupling in the control and learning of a visuomotor tracking pattern. The strength of perception-action coupling was modified by feedback, visuomotor mapping, perceptual pattern, and workspace framework. The differential strength of perception-action impacted the production of tracking accuracy and stability differentially among the various visuomotor tracking patterns and the learning of a new visuomotor tracking pattern.

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