

Learning a Single Joint Perception–Action Coupling: A Pilot Study



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Purpose: This study examined the influence of visuomotor congruency on learning a relative phase relationship between a single joint movement and an external signal.

Methods: Participants (N=5) were required to rhythmically coordinate elbow flexion-extension movements with a continuous sinusoidal wave (0.375 Hz) at a 90° relative phase relationship. The congruent group was provided online feedback in which the elbow angle decreased (corresponding to elbow flexion) as the angle trajectory was moving up, and vice versa. The incongruent group was provided online feedback in which the elbow angle decreased as the angle trajectory was moving down, and vice versa. There were two practice sessions (day 1 and 2) and each session consisted of 6 trials per block (5 blocks per session). Retention tests were performed 24 hours after session 2, and only the external sinusoidal wave was provided. Repeated ANOVAs were used for statistical analysis.

Results: During practice, the congruent group was significantly less variable than the incongruent group. Phase variability in the incongruent group did not significantly change across blocks, while variability decreased significantly in the congruent group. In retention, the congruent group produced the required 90° relative phase pattern with significantly less phase variability than the incongruent group.

Conclusions: Congruent visual feedback facilitates learning. Moreover, the deprivation of online feedback does not affect the congruent group but does affect the incongruent group in retention.

Keywords: Visuomotor tracking, Congruency, Perception-action, Coordination strategy

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1. Introduction

The question of how perceptual information, especially visual information, plays a role in voluntary motor control has been investigated intensively.¹⁻⁴ Understanding how visual information contributes to the control of motor performance will provide critical insights into the production of stable perception-action couplings. For instance, a bimanual circle tracing study showed that compatibility between the hands' tracing direction and the direction of visual stimuli displayed between the traced circles influenced the stability of coordination patterns. Other studies have demonstrated that manipulations of visual information during performance of an interlimb coordination task could stabilize or destabilize a coordination pattern.^{5,6} Bogaerts

et al⁵ required subjects 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 (in Experiment 1). Results showed that the transformed visual feedback did not influence an in-phase pattern (both hands moving in- or outward together) whereas the incongruent feedback stabilized an anti-phase pattern (both hands moving in the same direction) when the transformation produced a mirror image pattern. These findings show that the stability of perception-action couplings can be influenced through the congruency manipulation of visual information. Moreover, in a multifrequency coordination task, Mechsner et al⁷ found that difficult coordination patterns could easily be performed with

simple visual transformations. Thus, studies investigating the effect of visual transformation have focused on the short term adaptation of spatial performance in the motor system and coordination between limbs.^{5,6} Few studies, however, have addressed the question of how transformed visual information contributes to learning specific perception-action couplings.

The present study utilizes the tracking of a sinusoidal signal to examine the coordination dynamics (stability and loss of stability) of learning novel perception-action couplings. Tracking performance refers to the coordinate movements of a limb with an external signal. Many scientists and engineers have researched human tracking performance to investigate human visuomotor control and to develop ergonomically designed devices.^{8,9} Recently, some researchers have applied a dynamical systems approach to the issue of visuomotor tracking performance.¹⁰⁻¹² According to this approach, the perceptual motor system can be modeled as coupled nonlinear oscillators described in terms of a few relevant variables. For instance, experimental findings and modeling of rhythmic bimanual in-phase and anti-phase finger movements have shown that the relative phase relationship between limbs acts as an order parameter and movement frequency as a control parameter.¹³ Many bimanual experiments have demonstrated that in-phase (0°) coordination is more stable than anti-phase (180°) coordination. A key finding is that the anti-phase pattern exhibits critical fluctuations before a spontaneous phase transition to the in-phase pattern as movement frequency increases.¹⁴ When producing the in-phase pattern its stability across movement frequency plateaus remains constant. Similar behaviors predicted by the HKB model have also been found in single joint tracking of a continuous sinusoidal wave.¹² Work by Tass et al¹¹ showed that delay-induced transitions occur in a visually guided tracking movement. Furthermore, a recent study revealed that a 90° relative phase tracking of a sinusoid signal was less stable compared to in- and anti-phase tracking.¹⁰ It should be noted that based on the attractor landscape of the HKB model, 90° is a 'repeller' that pushes the system towards other attractors, either 0° or 180° . Consequently, this suggests that learning may be required to produce a 90° relative phase tracking pattern as a stable pattern in relation to either in- or anti-phase tracking patterns. Learning studies adapting the coordination dynamics approach have focused on both interlimb and intralimb coordination.¹⁵⁻¹⁸ These studies have shown that learning a

required relative phase pattern takes the form of a phase transition in the effector's coordination landscape. The repeller at 90° was stabilized with practice, resulting in a new attractor emerging in the attractors' coordination landscape. The qualitative change (phase transition from repeller to stable fixed point) associated with learning was expressed as the result of competitive and cooperative processes linked to the system's intrinsic dynamics.¹⁵⁻¹⁹ No work from the coordination dynamics approach has been directed at understanding the learning processes associated with tracking an external signal that is continuously changing.

The purpose of this pilot experiment was to address the effect of visual transformation on learning the perception-action coupling of a continuous limb motion to a continuous external signal. The main hypothesis of this study was that compatible (congruent) visual feedback of a limb's actual movement will enhance learning, whereas any type of transformed (incongruent) visual feedback of a limb's motion will produce deterrent effects on learning. This hypothesis would be accepted if the quality of learning is different between different visuomotor congruency conditions.

II. Methods

1. Subjects

A total of five undergraduate students (2 males and 3 females) volunteered to participate in this pilot 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. Two participants (1 male and 1 female) were randomly assigned to a congruent feedback group and three participants (1 male and 2 females) were assigned to an incongruent feedback group.

2. Apparatus and procedures

Participants were seated on a height-adjustable chair and were facing a computer monitor (Figure 1A). The participant's elbow was placed on the table in a supine position. Participants were asked to place the longitudinal axis of their upper arm at about 45° to the surface of the table (Figure 1A). The computer monitor was used to display the external tracking signal, online feedback of the participant's tracking motion, and an

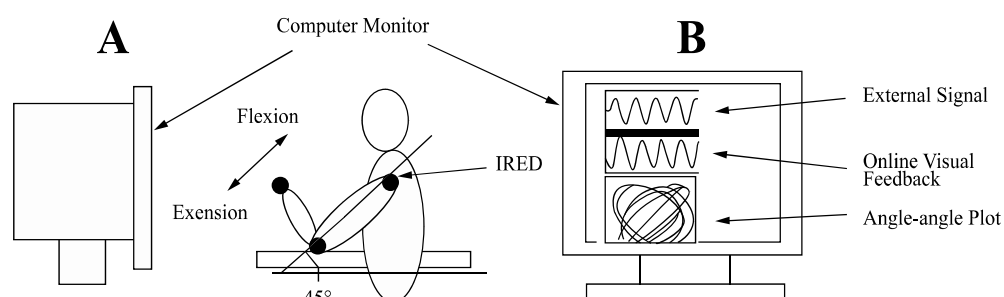


Figure 1. A) Experimental setup. A participant was seated on a chair and was facing to a computer monitor. The participant's elbow was placed on the table in a supine position. B) Computer screen displaying the external tracking signal (top), online visual feedback (middle), and angle-angle plot (bottom).

angle-angle plot (the tracking signal vs. the limb's motion) (Figure 1B). The sinusoidal tracking signal was produced with an AFG320 arbitrary function generator (Tektronix®, SONY). The oscillation frequency was set at 0.375 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) attached to the arm. Three IREDs were mounted as follows: 1) attached to a dowel held in the hand, 2) lateral epicondyle of the elbow, and 3) acromion process of the shoulder (Figure 1A).

Participants were required to rhythmically coordinate elbow flexion-extension movements to a continuous sinusoidal wave at a required relative phase relationship. There were two visuomotor congruency groups, a congruent condition group (visual information representing the actual limb movement) and an incongruent condition group (visual information representing the limb movement transformed by 180°) (Figure 2). The

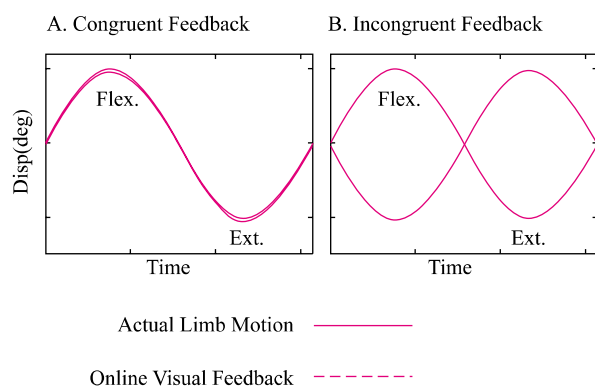


Figure 2. Two visual congruency conditions. A) The congruent condition is that online visual feedback represents the actual limb motion. B) The incongruent condition represents a 180° transformation between online visual feedback and the actual limb motion

congruent group was provided online visual feedback in which the elbow angle moved congruently to the sinusoidal signal, i.e., rotation of the forearm upward (flexion) produced an upward motion of the elbow angle on the screen (Figure 2A). The incongruent group was provided online feedback in which the elbow angle moved incongruently with the sinusoidal wave, i.e., rotation of the forearm upward (flexion) produced a downward motion of the elbow angle on the screen (Figure 2B). Thus, visuomotor congruency was only defined by the relationship between the actual limb movement (motor component) and its visual feedback (visual perception component).

1) Pre-practice session. Prior to the practice of the 90° relative phase pattern, pre-practice trials were performed. These trials consisted of 3 trials (9 trials total) for 3 different relative phase patterns, an in-phase (0°), an anti-phase (180°), and the to-be-learned 90° relative phase pattern (Figure 3). The relative phase patterns were defined by the relationship between the online visual feedback and the external signal. The in-phase pattern required the elbow flexion and extension peaks to be congruent with the peaks and valleys in the external tracking signal (Figure 3A). The anti-phase pattern required the elbow's peak flexion to coincide with a valley in the external signal, while the elbow's peak extension coincided with a peak in the external tracking signal (Figure 3B). The 90° relative phase pattern required the elbow's peak (or valley) to coincide with a zero-crossing in the external signal (Figure 3C). Participants were given 20 seconds of practice to familiarize themselves with the production of the joint motion displayed on the computer screen. Again, online visual feedback was different between visual feedback groups. An angle-angle plot of the tracking signal vs. the limb's motion was not provided as feedback in the

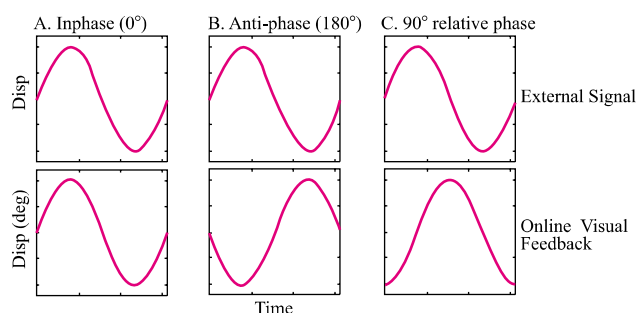


Figure 3. Three relative phase patterns characterized by the relationship between an external tracking signal and online visual feedback.

pre-practice trials.

2) Practice sessions. Practice session 1 was initiated immediately after the nine pre-practice trials. Practice sessions 1 (day 1) and 2 (day 2) consisted of 6 trials per block (36 practice trials per session). Participants were required to rhythmically coordinate elbow flexion-extension movements to a continuous sinusoidal wave at a 90° relative phase relationship (Figure 3C). The elbow angle trajectory was provided concurrently during a trial with the sinusoidal signal, and the angle-angle feedback plot was provided as terminal feedback after a trial. A circle in the angle-angle plot portrayed the required 90° relative phase relationship between the tracking signal and the participant's limb motion.

3) Retention. Retention was performed on day 3. The practicing individuals performed 3 trials (9 trials total) for each of the 3 different relative phase patterns, in-phase, anti-phase, and 90° relative phase. Only the external sinusoidal wave was provided with no online visual feedback of the elbow's motion and no terminal angle-angle plot.

3. 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. Dependent variables included relative phase and relative phase variability. A relative phase was computed to characterize the perception-action coupling relationship between the external signal and the elbow joint. A continuous relative phase was calculated as $\phi_C = \theta_{\text{external}} - \theta_{\text{elbow}}$. For each signal i an individual phase angle was 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. The in-phase pattern was characterized by a continuous

relative phase of $\phi_C \approx 0^\circ$ while a value of $\approx 180^\circ$ characterized the anti-phase pattern. 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. A relative phase error ($\phi_{AE} = \phi_{\text{req}} - \phi_C$) was computed and this score was used to evaluate learning. The relative phase standard deviation (ϕ_{SD}) provided a measure of pattern stability.

4. Statistical analysis.

The dependent variables from the pre-practice session were analyzed in a 2 Group (congruent, incongruent) \times 3 Pattern (0°, 180°, 90°) ANOVA with Pattern as a repeated measure. For the practice session, all four dependent variables were analyzed in a 2 Group \times 2 Day (day 1, day 2) \times 6 Block (1, 2, 3, 4, 5, 6) ANOVA with the last two factors repeated. To check if learning was maintained in the retention test, the last three trials for practice session 2 were compared to the three retention trials of the to-be-learned 90° pattern in a 2 Group \times 2 Session (last 3 trials in practice session day 2, retention trials of the 90° pattern) ANOVA with Session as a repeated measure. The retention data were analyzed in a 2 Group \times 3 Pattern ANOVA with the last factor repeated.

III. Results

1. Pre-practice Session

A representative pre-practice trial of the to-be-learned 90° relative phase pattern is shown in Figure 4A. The angle-angle plot (note that the angle-angle plot was not provided to participants in the pre-practice trials) demonstrates that the to-be-learned 90° relative phase was unstable prior to practice. The analysis of the phase variability data revealed that tracking was most variable when the to-be-learned 90° relative phase pattern was attempted, and that tracking was less variable when the 0° relative phase pattern was attempted, $F(2, 6) = 5.93$, $p < 0.05$ (Figure 5B). Neither main effects of Group nor interactions of Group \times Pattern were found in the AE and phase variability data from the pre-practice trials ($p > 0.05$ for both).

2. Practice Session

The trials plotted in Figure 4 show that practice improved the tracking performance of the required 90° relative phase for congruent (Figure 4B) and incongruent (Figure 4C) groups.

However, the congruent group ($\phi_{AE}=17.6^\circ$, $SD=6.1^\circ$) produced a mean tracking relative phase significantly closer to the required relative phase compared to the incongruent group ($\phi_{AE}=25.2^\circ$, $SD=8.3^\circ$), $F(1, 3)=37.26$, $p<0.01$. In the analysis of phase variability, a significant main effect of Block, $F(5, 15)=5.79$, $p<0.01$, and a significant interaction of Group \times Block, $F(5, 15)=3.05$, $p<0.05$, were found. Post-hoc tests of the Block effect revealed that tracking performance in Block 1 was significantly more variable than in the other 5 blocks (Figure 5B). Moreover, post-hoc tests of the Group \times Block interaction revealed that the congruent group produced less variable tracking performance than the incongruent group from Block 2 through Block 6 (Figure 5B). In addition, the variability in the incongruent group was constant across blocks, while the variability values were reduced in the congruent group from Block 1 to Block 6 (Figure 5B).

Figure 4B shows a representative trial of a visually congruent lag tracking pattern that represents an elbow trajectory following an external signal, Figure 4C depicts a representative trial of a visually incongruent lead tracking pattern representing an elbow trajectory occurring before an external signal. Without any explicit instruction two coordination patterns were found in the relationship between the external signal and the elbow angle trajectory to perform the same goal. Interestingly, participants chose mostly the lag pattern (98.3%) to achieve the task goal.

3. Retention Session

Figure 4D is a representative retention trial from the congruent group, and figure 4E is a representative retention trial from the incongruent group (Note: both the online visual feedback and angle-angle plot feedback were not provided in retention.). The trial practiced with the congruent visual feedback was more circular on the angle-angle plot compared to the trial practiced with the incongruent visual feedback.

Analysis of relative phase data did not detect any main effects or interactions in the comparison between the last three trials of the practice session and the to-be-learned pattern trials of the retention session ($p>0.05$ for all). The retention trials ($\phi_{SD}=30.35^\circ$, $SD=13.1^\circ$) were more variable compared to the last three trials of the practice session ($\phi_{SD}=23.4^\circ$, $SD=8.7^\circ$), $F(1, 3)=10.6$, $p<0.05$.

As shown in Figure 5B, the in-phase and anti-phase data for the incongruent group had a much larger error compared to the

congruent group in retention. The congruent group ($\phi_{AE}=11.1^\circ$) was characterized by a smaller ϕ_{AE} compared to the incongruent group ($\phi_{AE}=60.5^\circ$), $F(1, 3)=42.75$, $p<0.01$ (Figure 5A). A significant main effect of pattern was also found, $F(2, 6)=12.11$, $p<0.01$, and post-hoc tests revealed that the 90° relative phase pattern had the smallest ϕ_{AE} (Figure 5A). Analysis of the phase variability data revealed that the congruent group ($\phi_{SD}=12.6^\circ$) was significantly less variable than the incongruent group ($\phi_{AE}=38.2^\circ$), $F(1, 3)=18.1$, $p<0.05$ (Figure 5B). For further analysis of the tracking performance in retention, we conducted a 2 Group \times 2 Pattern (in-phase, anti-phase) analysis of the ϕ_{AE} and ϕ_{SD} data. Analysis of the ϕ_{AE} data revealed that the congruent group ($\phi_{AE}=12.8^\circ$) produced the in- and anti-phase patterns with significantly less error than the incongruent group ($\phi_{AE}=78.6^\circ$), $F(1, 3)=24.03$, $p<0.05$ (Figure 5A). The test of the ϕ_{SD} data also revealed that the congruent group ($\phi_{SD}=9.3^\circ$) was significantly less variable than the incongruent group ($\phi_{SD}=38.5^\circ$) when producing the in- and anti-phase trials, $F(1, 3)=26.58$, $p<0.05$ (Figure 5B). The 90° relative phase retention trials were analyzed solely as a function of Group the test revealed that the congruent group ($\phi_{AE}=7.8^\circ$) was characterized by a smaller ϕ_{AE} than the incongruent group ($\phi_{AE}=24.3$), $F(1, 3)=14.24$, $p<0.05$ (Figure 5A). However, analysis of the ϕ_{SD} data showed that the difference did not reach significance.

IV. Discussion

The congruent group demonstrated that the unstable repeller at the to-be-learned 90° relative phase was stabilized with practice. Both the practice and retention results revealed that the incongruent group did not stabilize the to-be-learned 90° relative phase pattern. These results support the hypothesis that congruent visual feedback facilitates the learning process. The retention session illustrates that the loss of concurrent visual feedback does not affect the congruent group.

The striking finding in the present study is that the retention performance is clearly influenced by which visuomotor congruency is utilized during practice. In retention of the 90° pattern, the congruent group's phase variability was maintained compared with their own performance on practice trials. In contrast the incongruent group's performance during retention

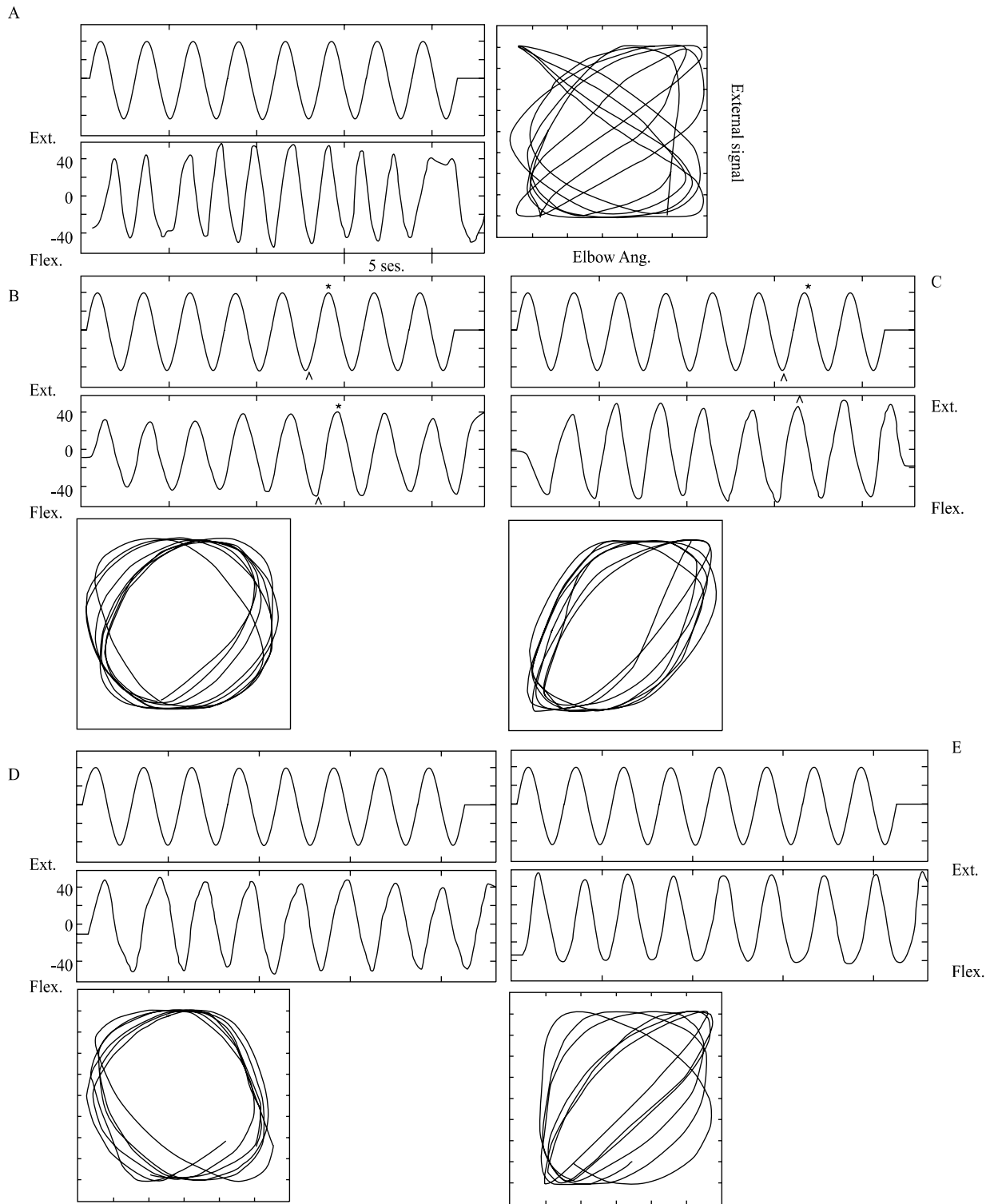


Figure 4. Representative examples of the to-be-learned 90° pattern in the pre-practice (A), practice session (B and C), and retention session (D and E). Plots show tracking performances over time (tracking signal and online visual feedback of elbow motion) as well as angle-angle plots (external signal vs. elbow angle). B) and D) represent tracking performances in the congruent group. A), C), and E) represent tracking performances in the incongruent group.

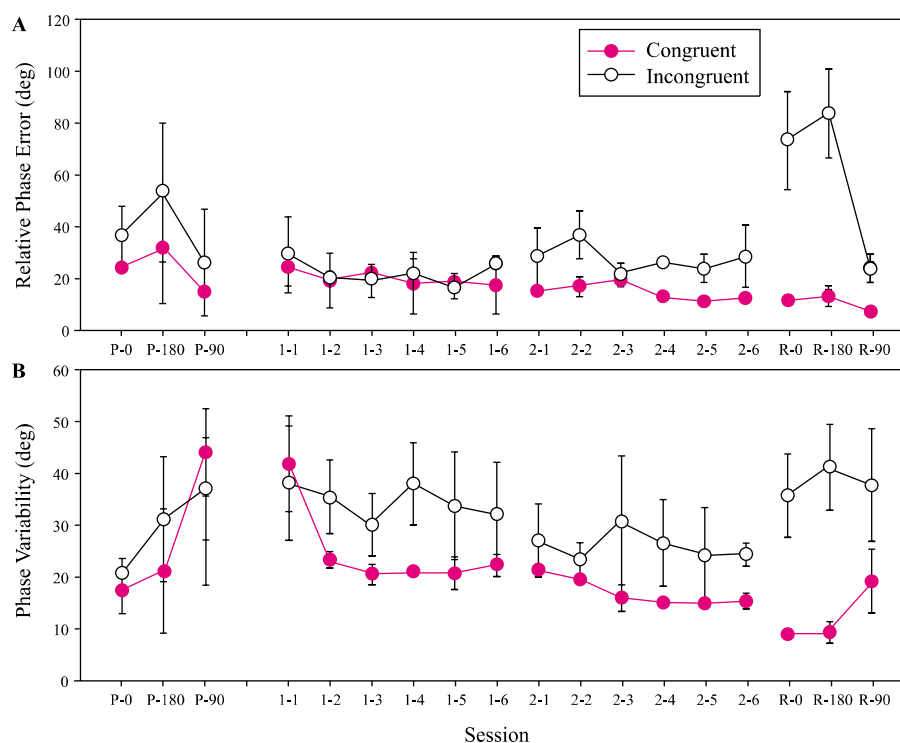


Figure 5. Mean relative phase (A) and phase variability (B) are plotted as a function of session (P-: pre-practice, 1-1: day1-block1, R-: retention) and group.

was characterized by relatively higher variability compared with what was produced at the conclusion of practice. This suggests that the incongruent group was unable to stabilize the pattern, whereas the congruent group did stabilize the 90° pattern with practice. Although the retention test did not provide participants with online feedback of the joint angle trajectory, the in- and anti-phase pattern produced by the congruent group were less variable compared to pre-practice and compared to the incongruent group. This suggests that learning the 90° relative phase pattern enhances the in- and anti-phase patterns, consistent with the findings of Buchanan.¹⁷ In the incongruent group, the absence of online feedback severely degraded the in- and anti-phase patterns compared with the pre-practice trials, suggesting that the incongruent group did not significantly benefit from practice. A question that arises here is why the incongruent group was affected by the deprivations of visual feedback even in the stable in- and anti-phase patterns. The first explanation might be that the participants in the incongruent group did not actually know or learn the perceptual structures of the patterns. However, the in- and anti-phase patterns are perceptually the most stable patterns and do not require any practice to perceive.²⁰ So the first explanation would not extend

to the most stable in- and anti-phase patterns, but does extend to the 90° relative phase pattern. A second explanation could be that the participants in the incongruent group did not adapt the visuomotor mapping. Although the participants practiced for a significant period of time to adapt the incongruent visuomotor mapping, the required movement pattern and the incongruent visuomotor mapping interacted in a detrimental way when a participant was required to learn the pattern and mapping simultaneously.

The other interesting finding of this study is the fact that participants chose largely the lag pattern to achieve the task goal without any explicit instruction. Since the present experiment required coordination of a limb with an external signal, exploring the question of why the specific pattern emerges may provide an insight into how humans utilize perceived information to achieve a certain movement goal. One possible explanation is that one aspect of the visual structure of the required pattern is more easily perceived than some other aspect of the same visual structure. In other words, the lag pattern was characterized by an iso-directional pattern, which means that a participant produced a peak (and valley) in the 'same direction' a certain time after a peak (and valley) in the external signal

occurred (Fig 4B, note the pattern of ^ and *). The few trials of the lead pattern were characterized by a peak in the 'opposite direction' a certain time after a valley in the external signal occurred. This would be characterized as a hetero-directional pattern (Fig 4C, note the pattern of ^ and *). It is well known that the structure of iso-directional motion is less variable than a (perceived) motion moving in a different direction.^{5,7} Thus, an issue that arises is how a pattern is selected from possibilities given environmental conditions and/or a system's internal conditions. A further study is warranted to investigate additional coordination strategies.

V. Conclusion

In conclusion, this study shows that congruent visual feedback facilitates learning. Moreover, the deprivation of online feedback does not affect the congruent group but does affect the incongruent group in retention.

This pilot study presents an insight about control and learning of an environment-actor coordination skill. Follow-up studies will provide important data with which to develop rehabilitation or training programs to persons with an impaired perceptual motor coordination ability (e.g., elderly people, developmental disorder children, neurological patients), and to persons with highly required perceptual motor coordination skills (e.g., car drivers, pilots, sportsmen).

Author Contributions

Research design: Ryu YU

Acquisition of data: Ryu YU

Analysis and interpretation of data: Ryu YU

Drafting of the manuscript: Ryu YU

Administrative, technical, and material support: Ryu YU

Research supervision: Ryu YU

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