

Movement Interference During Action Observation as Emergent Coordination

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Abstract

Previous research has demonstrated that when an actor coordinates with spatially incompatible movements of another individual that motor interference occurs—the rhythmic arm movements of the actor exhibit increase movement variability in the plane orthogonal (non-instructed) to the instructed plane of motion. Here we examine whether this motor contagion reflects not error but the spontaneous recruitment of additional task-specific movement degrees of freedom employed to withstand increasing task difficulty. Participants coordinated congruent and incongruent forearm movements with a confederate moving at a fast, moderate, and slow target frequency. Examining the variability in the non-instructed plane revealed oscillatory non-instructed plane movements that were coordinated with the instructed plane movements of the confederate. The results suggest motor interference during incongruent coordination can be understood as an emergent, task-specific property of the coordination goal.

In the performance of everyday activity the patterning of an individual's limb and body movements are constantly influenced by the observed movements of other individuals [e.g., 18, 20]. Such action imitation or coordination is hypothesized to be the result of the pre-motor cortex representing action execution and observation together in a common code [8, 10, 15]. Neural support for this hypothesis has come with the discovery of mirror neurons—cells in area F5 of the pre-motor cortex of Macaque monkeys that fire when a monkey both executes and observes a particular action—and the consequent neuroscience studies that suggest there is a similar “mirror neuron” system in humans [see 17 for a review].

Strong evidence for a common coding theory of action imitation and coordination stems from discovering that the action onset times of discrete movements (e.g., finger lifting, grasping an object with the hand) are facilitated by the observation of compatible movements and delayed by the observation of incompatible movements—incompatible in terms of movement effector or direction [3, 4]. Recently, similar compatibility effects have been examined during continuous movement synchronization [7, 12, 21]. In these latter studies, participants were instructed to perform rhythmic arm movements in the horizontal or vertical planes, and to synchronize these movements with the metronome-paced horizontal or vertical movements of a confederate. Congruent conditions corresponded to the participant moving in that same plane as the confederate (i.e., the participant and confederate moved horizontally or vertically), whereas incongruent conditions corresponded to the participant moving in the plane orthogonal to the confederate (e.g., the participant moved horizontally and the confederate moved vertically). In general, the variance of the participant's movements in the non-instructed plane of motion (e.g., the vertical plane when instructed to produce horizontal movements) was found to be enhanced

in the incongruent compared to congruent coordination. The same compatibility effect has also been observed when participants synchronize their movements with a computer stimulus [21].

Motivated by discrete movement compatibility research, the increased variance in the non-instructed movement plane has been interpreted as an *interference* effect or motor production *error*, and is hypothesized to be the result of motor contagion [2, 21]. It is presumed that observing the movement of the confederate leads to the activation of the pre-motor areas that correspond to the production of that movement, irrespective of whether the observed movement is compatible with the intended movement. Thus, when the participant observes the confederate producing an incongruent movement, the motor program or representation associated with the observed movement is assimilated or interferes with the outgoing motor output for the intended movement.

Here we more closely investigated this motor contagion phenomenon by examining whether the observed increase in movement in the non-instructed plane should be construed as error. The question is whether the evoked non-instructed movements have structure and are organized as part of the control structure formed to coordinate the limbs. The recruitment of additional movement *degrees-of-freedom* (*df*) has been shown to be an essential source of task-specific flexibility, whereby previously quiescent *df* are employed to stabilize coordination [5, 6]. Research by Fink and colleagues [6] has demonstrated that during bimanual rhythmic movements in the sagittal plane movements in the frontal plane emerge at high frequencies of oscillation in order to stabilize the interlimb coordination. They argue that such recruitment of additional planar motion complements phase transitions as a source of coordinative flexibility. Accordingly, the current study explored whether increased non-instructed plane movements during incongruent coordination are patterned to reflect the spontaneous recruitment of a non-

instructed, yet task-specific, *df* to stabilize the intended coordination. Participants performed congruent and incongruent forearm movements with a confederate at three target frequencies. We anticipated that incongruent coordination would be less stable than congruent coordination, particularly at higher movement frequencies, and that increases in non-instructed plane variability during incongruent conditions would be structured into coherent and coordinated oscillations that reflect the recruitment of additional *df*.

Method

Participants. Nine undergraduate students from Colby College participated in the experiment.

Task and materials. Participants coordinated movements of the right-forearm (right index finger extended) in either the horizontal (frontal) plane or vertical (sagittal) plane, with horizontal or vertical right-forearm movements of a confederate¹. Participants stood 1.5 m away (toe-to-toe) from the confederate. A small 1 × .5 cm sensor was fixed to the tip of the participant's and confederate's index finger and the movements of the participant and confederate were recorded at 120 Hz with 0.01 mm spatial resolution using the Liberty⁸ magnetic motion tracking system (Polhemus Ltd, VT).

The confederate performed complete cycle movements at three frequencies of oscillation, 1.25, .71, and 0.5 Hz (periods of .8, 1.4, and 2.0 s respectively). A metronome beat was presented to the confederate through headphones to ensure that they produced the correct frequency of oscillation. The confederate timed their movements so that the right-most endpoint of the horizontal movement and the top-most endpoint of the vertical movement coincided with the metronome beat. The instructed plane movements of the participant and confederate were crossed to create two congruent and two incongruent movement conditions (Figure 1). For both

conditions, the participant was instructed to synchronize with the confederate in an inphase manner. Incongruent inphase was defined as a correspondence of the top-most position of the vertical movements with the right-most position of the horizontal movements. The participants also performed six baseline trials, one horizontal and one vertical trial for each target frequency, which involved the participants moving alone after coordinating with the confederate for 10 s.

Procedure. Participants were informed that they would be required to coordinate horizontal and vertical forearm movements about the elbow with horizontal and vertical forearm movements of a confederate at a fast, moderate, and slow tempo. They were given several minutes to practice the different direction and congruency conditions.

Participants completed three blocks of six trials. A different target frequency was used for each block, with the order of the trial blocks counterbalanced across participants. For the first four trials of each block, participants completed the two congruent and two incongruent trials in a random order. For the last two trials of each block, participants completed the horizontal and vertical baseline trials for that frequency of oscillation (the order of the baseline trials was randomized). Each trial was 35 s long and movement recording started 10 seconds after the participant was correctly coordinating.

Signal Processing

The participant and confederate position time-series in the instructed and non-instructed planes for each trial were centered around zero and low-pass filtered with a cutoff frequency of 10 Hz using a Butterworth filter.

The SD of relative phase ($SD\phi$) was employed to evaluate the stability of the coordination between movements in the participants' and confederate's instructed motion planes. Using the Hilbert transform, the instantaneous phase [e.g., 14] of the movement time-series was

calculated for each experimental trial. The difference between the phase angles of the two movements was then computed ($\phi = \theta_{confederate} - \theta_{participant}$), and the $SD\phi$ was calculated from the resulting relative phase time series. We expected congruent coordination to be more stable (have a lower $SD\phi$) than incongruent coordination.

A number of measures were used to evaluate the motion in the non-instructed plane. In replication of the previous research, the SD (in cm) of the participants' movements in non-instructed plane was calculated for each trial, with the expectation that the SD of the non-instructed plane would be greater for incongruent compared to congruent coordination. To evaluate the rhythmic nature of the non-instructed motion a spectral analysis was performed on the non-instructed plane time-series. The distributions of the spectral power densities for the non-instructed movement time-series were calculated for each trial between 0 to 2 Hz. The average power of the two frequency bins centered around the corresponding target frequencies were extracted from these distributions for statistical analysis. It was expected that the spectral power of the non-instructed plane movements would reveal greater oscillatory components in the form of spectral peaks for incongruent compared to the congruent coordination.

To evaluate whether the movements in the non-instructed plane were task-specific and coordinated with the movements of the confederate in the instructed plane we employed standard measures of entrainment [16, 19]. Cross-spectral coherence was used to evaluate the correlation of the movements that occurred between the non-instructed plane of the participant and the instructed plane of the confederate. The coherence at the peak frequency of the confederate's movement time-series (i.e., the target frequency) was used as index of the degree of coordination. Additionally, we calculated the distribution of relative phase angles formed between the non-instructed movements of participant and the instructed movements of the

confederate to evaluate the qualitative nature of the possible entrainment. These distributions consisted of the percentage of occurrence of the non-instructed-to-instructed relative phase angles (calculated as above) in nine 20° regions of relative phase between 0° and 180°. Phase-entrainment is indicated by a concentration of relative phase angles near 0° and 180°, which correspond to the stable attractor states for interpersonal interlimb coordination [18]. We expected that the participants' the non-instructed plane movements would be entrained to the instructed movements of the confederate and that this entrainment would be stronger during incongruent compared to congruent coordination.

Results

Two horizontal and two vertical incongruent trials for the 1.25 Hz target frequency were dropped and replaced with the condition means because the instructed pattern of coordination was not maintained. The SD of movement in the non-instructed plane, and the spectral power of the participants' non-instructed plane movements at the corresponding target frequency were analyzed using 3 (target frequency) \times 3 (congruency: congruent, incongruent, baseline) \times 2 (instructed plane) repeated measures ANOVAs. Because the baseline trials were irrelevant to the measures of coordination (no confederate movements), $SD\phi$ and coherence were analyzed using 3 (target frequency) \times 2 (congruency: congruent, incongruent) \times 2 (instructed plane) repeated measures ANOVAs. The distributions of the relative phase were analyzed using a 9 (phase region: 0-20, 21-40 ..., 161-180) \times 3 (target frequency) \times 2 (congruency) \times 2 (instructed plane) repeated measures ANOVA.

Stability of instructed coordination. Consistent with the stability of the coordination decreasing as the target frequency increased and incongruent coordination being less stable than congruent coordination, the analysis of $SD\phi$ yielded main effects for target frequency, $F(2, 16)$

= 40.15, $p < .01$, and congruency, $F(1, 8) = 31.85$, $p < .01$. As can be seen from Figure 2a, participants exhibited a significantly higher $SD\phi$ for the 1.25 Hz target frequency compared to the .71 Hz and 0.5 Hz target frequency (Turkey HSDs, both $p < .05$) and for incongruent compared to the congruent coordination. There were no other significant effects (all $p > .05$).

Variability of non-instructed plane. The analysis of the SD of movement in the non-instructed plane yielded a significant effect for congruency, $F(2, 16) = 8.80$, $p < .01$, and a significant congruency \times plane interaction, $F(2, 16) = 10.89$, $p < .01$ (all others $p > .20$). Consistent with previous research, more variability was observed for the incongruent compared to the congruent trials [12], with this difference being more pronounced when the instructed movement was in the horizontal plane compared to the vertical plane [21]. Analysis of the simple effects of the interaction suggest that participants produced less non-instructed plane variability than baseline for the congruent conditions in both planes (vertical plane: $F(1, 8) = 9.63$, $p < .05$; horizontal plane: $F(1, 8) = 9.63$, $p = .08$) but greater non-instructed plane variability than baseline for the incongruent conditions only in the horizontal plane, $F(1, 8) = 9.57$, $p < .05$, (Figure 2b).

Spectral power of the target frequency in the non-instructed plane. Inspection of the example time series and distributions of the spectral power densities for the non-instructed movement time-series displayed in Figure 3 reveals an oscillatory component with a frequency specific to the target frequencies produced by the confederate. Analysis of the mean height of these spectral peaks at the target frequencies yielded a significant main effect of congruency, $F(1, 8) = 10.89$, $p < .01$, with the non-instructed movement time-series exhibiting higher peaks at the target frequencies for the incongruent compared to the congruent condition (Figure 2c). There were no other significant effects (all $p > .05$).

Non-instructed-to-instructed coordination. The analysis of coherence yielded a significant main effect for congruency, $F(1, 8) = 7.37, p < .05$. Greater magnitudes of coherence were found for the incongruent trials compared to the congruent trials (Figure 2d), indicating that greater non-instructed-to-instructed entrainment occurred between the participant and the confederate for incongruent conditions. The analysis of the distributions of relative phase yielded a significant main effect of phase region, $F(8, 72) = 13.75, p < .01$, and a significant three-way interaction between phase-region, congruency, and plane, $F(1, 8) = 2.03, p < .05$. As can be seen from Figure 4, more relative phase angles were concentrated around 0° and 180° , with the concentration greatest for the incongruent condition and when participants were instructed to produce movements in the horizontal plane. Analysis of the interaction's simple effects yielded a significant main effect of phase region for both the horizontal, $F(1, 8) = 2.03, p < .05$, and vertical, $F(1, 8) = 2.03, p < .05$, planes of motion, but only a significant congruency \times phase region interaction for the horizontal plane, $F(1, 8) = 2.03, p < .05$.

Discussion

The current study examined whether increased non-instructed plane movement during incongruent coordination is structured and reflects the spontaneous recruitment of a non-instructed df as a flexible response to task demands. In support of this hypothesis, the results demonstrated that increases in non-instructed plane movement during incongruent coordination were not noise or error-like fluctuations, but rather were the consequence of coherent oscillations that contained a frequency component equal to the target frequency of the instructed plane of motion. These non-instructed plane oscillations were also found to be entrained to the instructed plane movements of the confederate, whereby the greater the amplified of non-instructed plane oscillations, the more correlated were the participant-confederate non-instructed-to-instructed

plane movements and the more non-instructed-to-instructed relative phase angles were observed near 0° and 180° . Although it is unclear why this result was more pronounced when participants' were instructed to move in the horizontal plane—but it is likely due to a difference in the biomechanical flexibility of forearm movements in frontal and vertical planes—such intermittent inphase and antiphase coordination indicates that the non-instructed-to-instructed entrainment was unintentional. More to the point, the increased appearance of coherent oscillations in the participants' non-instructed plane movements occurred spontaneously. Such intermittent coordination is characteristic of the spontaneous coordination that naturally occurs between the limb movements of two co-actors or between the limb movements of an individual and an environmental rhythm or computer stimulus [18], and is 'relative', rather than 'absolute', due to a reduction in the saliency of, or attention to, the relevant movement kinematics [16, 19].

As expected, the $SD\phi$ of the instructed coordination was found to be greater for incongruent compared to congruent coordination. Consistent with incongruent coordination being less stable than congruent coordination, this finding raises that possibility that the informational coupling is weaker for incongruent compared to congruent coordination due to limitations in the resolution of the information that specifies incongruent compared to congruent coordination [1, 23]. Beyond identifying that incongruent coordination is less stable than congruent coordination, this finding provided an additional base of support for the hypothesis that increased non-instructed plane movement during incongruent coordination reflects the spontaneous recruitment of the non-instructed movement df , as the recruitment of non-instructed df is more pronounced for weaker states of coordination [5, 6].

The spontaneous addition of another oscillator plane of motion in response to increasing task demands has been modeled by Fink et al., (2000) using a simple extension of the Haken-

Kelso-Bunz (9) model of interlimb coordination, in which the frontal and spatial components of two rhythmic limb movements are modeled as coupled self-sustained oscillators. This four-component model simulates the requisite relative phase behavior of the instructed planes of motion, as well as the patterning and increased recruitment of the non-instructed plane of motion as the stability of the coordination decreases. Future research should examine whether this model could be adapted to understanding the dynamics of congruent and incongruent interpersonal coordination, with the possibility that one could predict and understand the stability and patterning of both instructed and non-instructed movements using a single ‘unifying’ model. By employing a unidirectional coupling function this model might also account for differences in the patterning and stability of instructed and non-instructed movements during the congruent and incongruent coordination of an individual to a computer or robotic stimulus (12, 21). In addition to predicting a notable recruitment of non-instructed df of movement during incongruent coordination, it seems likely that an adapted version of the extended HKB model could also account for the comparatively small degree of non-instructed-to-instructed entrainment that was found to occur during congruent condition. The extended HKB model would predict recruitment of non-instructed df to stabilize coordination irrespective of spatial congruency given that the dynamics of both a congruent and incongruent coordination goal should dictate that movements in non-instructed df will, to greater or lesser degrees given the stability of the corresponding coordination, emerge in the realization of that goal [6].

In conclusion, the current experiment indicates that increased non-instructed plane movement during incongruent coordination is an emergent property of rhythmic coordination. By implicating this compatibility effect as a functional part of the coordination goal, the current findings also indicate that researchers should consider the coordination dynamics—

spatiotemporal patterning stability of movement—that constrain human movement when hypothesizing about the perceptual-motor process that underlie action imitation and coordination. This is not to say that there aren't important neurocognitive processes that underlie such perceptual-motor behavior. Indeed, the current results do not rule out a constructive (rather than error) based motor contagion or common-coding explanation. However, the results do suggest that hypotheses about what these neurocognitive processes do might be dramatically different if dynamical principles of self-organization are taken into account [11]. At a minimum, understanding the dynamic structure of human behavior will help guide the development of such hypotheses [13, 22, are examples] not only for action observation effects but also for perception-action phenomena generally.

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Endnote

¹ The confederate was blind to the true nature of the study. In replication of previous research (12, 24), we present the analysis of the participants' non-instructed plane movements. However, the structure of the confederate's non-instructed plane movements was similar to the participants' non-instructed plane movements.

Author note

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Figure Captions

Figure 1. Experimental conditions.

Figure 2. (a) $SD\phi$ for the instructed coordination. (b) SD of the participants' non-instructed plane movements. (c) Mean spectral power (dB/Hz) at the target frequency for the participants' non-instructed plane movements. (d) Non-instructed-to-instructed plane coherence.

Figure 3. Example instructed and non-instructed plane movement time-series for a participant instructed to coordinate with (a) congruent or (b) incongruent movements of a confederate. For (a) and (b) the instructed plane corresponds to movements in the horizontal plane and the non-instructed plane corresponds to movements in the vertical plane. (c) Spectral power distributions for the participants' movements in the non-instructed plane with frequency bins of .05 Hz from 0 to 2 Hz.

Figure 4. Relative phase distributions for non-instructed-to-instructed plane coordination.







