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Effect of Observed Biological and Non-biological Movement on Human Action and Coordination

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Effect of observed biological and non-biological movement on human action and coordination

Walter L. Campbell

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Abstract

Dynamical systems researchers have understood the stable patterning of interpersonal and non-biological environmental rhythmic limb coordination to be constrained by the self-organized entrainment processes' coupled oscillators. Recently, it has been demonstrated that an individual's rhythmic limb movements exhibit greater variability when viewing spatially incongruent biological limb movements, but not when viewing spatially incongruent non-biological movements. Some researchers have concluded that a 'mirror-neuron system' might mediate the intrinsic bidirectional link between perception and action underlying interpersonal, but not environmental, coordination (e.g., Kilner et al., 2003; Tognoli et al., 2007). The current study aimed to: 1) contest this recent finding; and 2) demonstrate that the self-organized entrainment processes of coupled oscillators can explain the differing influences of biological and non-biological movements. In the first experiment, participants intentionally coordinated arm movements with spatially congruent and incongruent arm movements of a confederate, a robotic image with computer generated movement, and a robotic image producing pre-recorded human movement. Results revealed more stable coordination for congruent and biological movement than incongruent and robotic movement, respectively. The second experiment investigated the influence of biological and non-biological movement on unintentional coordination. Consistent with dynamical systems theory, coordination was found in both biological and non-biological conditions.

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Effect of observed biological and non-biological movement on human action and coordination

Movement coordination is present at all levels of daily life. From the natural, unpracticed coordination that occurs between two friends walking and talking together to the skillful, trained coordination of lanky basketball players or quick-footed dancers, coordination plays an undeniable role in human social interaction. Despite not sharing a common cognitive or neural mechanism and common limbs, multiple individuals still come together in dynamic cooperative relationships binding them in a way that resembles a single organism's functioning (Asch, 1952; Newton, Hairfield, Bloomingdale, & Cutino, 1987). For such coordination to occur, there must be a perceptual link between these two separate acting systems. Further there must be a strong link between the perception and action processes of each interactant. Without such a link between perception and action, coordination among cognitively and psychically separate systems can not occur. The perception of another's actions, and the influence of this perception on one's actions, is what causes multiple systems to come together in synchrony.

The dynamic systems theory and the mirror systems theory are two popular explanations for the relationship between perception and action, and how this relationship can result in interpersonal coordination. According to mirror systems theory there are neurons in our brain that represent certain movements. These neurons fire when we observe or perform an action (Blakemore & Frith, 2005). The perception of an action causes firing in the same part of the brain as the performance of that action, and thus perception and action directly influence each other. On the other hand, dynamic systems theory states that all systems have a tendency to become coordinated with their

environment. Such coordination leads to a more stable state of existence—a system-environment equilibrium. Dynamic systems posits as long as there is sufficient perception of environmental rhythms, a system's actions will naturally come into self-organized coordination with what is perceived. Thus the basis for both theories is that when we perceive another person's movement, we are likely to coordinate with this movement.

Kilner, Paulignan, and Blakemore (2003) conducted a study on perceiving and making arm movements, and explained their results through the mirror systems theory. The present study aims to replicate their findings, and show that they can be better explained using the dynamic systems theory.

Mirror neurons and mirror systems theory

Mirror neurons refer to cells that were discovered in area F5 of the pre-motor cortex of Macaque monkeys that fire when a monkey both executes and observes a particular action (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996). Since the discovery of mirror neurons in monkeys, a number of functional magnetic resonance imaging (fMRI), positron emission tomography (PET), electroencephalography (EEG), and transcranial magnetic stimulation (TMS) studies have found evidence to suggest that a similar “mirror neuron” system might also exist in humans (Grezes, et al., 1998; Cochin, et al., 1999; Grezes, et al., 1999; Strafella & Paus, 2000; Buccino, et al., 2001; Iacobani et al., 2001; Aziz-Zadeh, et al., 2002; Muthukumaraswamy & Johnson, 2004).

Theoretically, the mirror neuron system is argued to account for why observing an action causes an automatic activation of brain areas normally associated with action execution (Press et al., 2005), whereby this neural activation represents itself behaviorally

through action imitation (Brass & Heyes, 2005). It is important to note, however, that this response is to general, not specific, aspects of the observed movement (Blakemore & Frith, 2005), whereby the mirror neuron system activates a motor prototype in the observer and not an “instant and accurate imitation” (Vogt & Thomaschke, 2006). In addition, because the amount and the effects of activation are directly related to the observer’s intention, mirror systems theory holds that activation of these neurons does not always elicit behavioral imitation. Indeed, activation in the premotor and parietal cortices is greatest when observers have the intent to imitate (Grèzes, Costes & Decety, 1999). Thus, when the intent to imitate is absent, witnessing movement either facilitates the execution of the witnessed movement or interferes with performance of a different movement (Press et al., 2005). This latter point defines a key prediction of mirror systems theory, namely, that observed movements that are qualitatively different from performed movements cause an interference effect. Specifically, because observed and performed movements activate the same neurons, an incompatibility between them is argued to impair movement. For instance, individuals instructed to either tap or lift their fingers, with a photo of either the movement they were to produce or the alternate movement as their signal to begin, exhibited significantly slower movement onset times when the photograph was of the alternate movement compared to the to-be-produced movement (Brass, Bekkering, & Prinz, 2001). Similar interference effects have been demonstrated in studies investigating bar grasping, opening and closing of hands, and arm swinging (Craighero, et al., 2002; Kilner, Paulignan, & Blakemore, 2003; Vogt, Taylor, & Hopkins, 2003; Blakemore & Frith, 2005).

Researchers have suggested that such interference effects should only occur when the observed movement is made by a human, or more specifically a biological conspecific (Blakemore & Frith, 2005; Kilner, Paulignan, & Blakemore, 2003). Drawing on research which demonstrates how infants, as early as 3 months old, are able to distinguish between dots moving in a human-like (biological) manner and those moving in a robotic (non-biological) manner (Bertenthal, 1993), these authors have claimed that the mirror system more effectively represents human movement, because the brain processes biological and non-biological motion differently. The distinction between biological and non-biological motion is partially explained by biological motion primarily being mentally processed in the STS (Grèzes, et al., 2001; Grossman & Blake, 2001; Grossman et al., 2000; Allison, Puce & McCarthy, 2000; Frith & Frith, 1999), which is also activated during motion performance. Although the area of the brain in which non-biological motion is processed has yet to be discovered, it does not appear to be processed in the STS, thus no interference effect would occur while witnessing robotic motion (Blakemore & Frith, 2005).

To verify this claim, Kilner, Paulignan, & Blakemore (2003) further examined the dependence of the interference effect on witnessing human motion. Participants made horizontal or vertical arm movements in the presence of a confederate (biological motion) or a robotic arm (non-biological motion), with four conditions for each. In two of the conditions, the movements of the participant and confederate/robot were congruent—both moved either horizontally or vertically. In the other two conditions, the movements of the participant and confederate/robot were incongruent—the participant moved

vertically while the confederate/robotic arm moved horizontally, or the participant moved horizontally while the confederate/robotic arm moved vertically. The subjects coordinated in time with the confederate or robotic arm's movements, regardless of congruency or direction, and the authors measured the end-point variability of the participant's movements in the plane opposite to the intended plane of movement. The results revealed an increase in end-point variability for the incongruent condition compared to the congruent condition, but only when the participant coordinated with the confederate—no difference was found between the congruent and incongruent conditions when the participant coordinated with the robot. Thus, an interference effect was only observed for incongruent human movement. The subjects perceptually represented a type of movement that was in opposition to the one they intended to make. Because this representation and action occur in the same neural location, the participant's action was hindered by the incongruent perception. On the other hand, robotic movement is represented in a different neural location than human movement, and thus perception of robotic motion had no effect on the participant's action. The interference effect was only present in the confederate condition, with almost no effect for the robotic condition.

Although the study by Kilner et al., (2003) suggests that there are separate neural representations for biological motion and robotic motion, more recent research has shown that the more non-biological motion resembles human movement, the more likely imitation (and thereby interference) is to occur (Press, Bird, Flach & Heyes, 2005). Participants in this study were required to open their hand while looking at a picture of either a human or robotic hand in an open/compatible position or a closed/incompatible

position. Although the human hand had a stronger effect on performance, making the robotic hand similar in size, color, and brightness to the human hand elicited both an imitation and interference effect. Thus, it is unclear if the Kilner et al (2003) findings are due to separate neural representations of a biological species and robotic creation.

There is a growing body of literature on the self-organized emergence of visual rhythmic coordination, according to which coordination between the movements of two systems emerges spontaneously so long as there is an informational link between the systems (Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Schmidt, Christianson, Carello, & Baron, 1994). Of particular relevance, is that this latter research has demonstrated how the human movements of one individual can become intentionally and unintentionally synchronized to the movements of another individual (biological) or environmental stimulus (non-biological) and that such coordination is constrained by the self-organized entrainment process of coupled oscillators. Under this understanding, increases in the variability of movement are not the result of 'interference' or different neuro-cognitive processes, but rather are the result of differences in the inherent and lawfully defined stabilities of the different movement patterns produced or the strength of the informational coupling that links the respective movements (Kelso, 1995; Kugler & Turvey, 1987). Thus the variability observed in the above mentioned studies for congruent and incongruent movements is a result of the inherent stabilities of these movement patterns, and the variability observed for biological and non-biological

movement is caused by the different coupling links between two biological systems and between a biological system and an environmental stimulus.

Dynamic systems theory

Dynamical systems theory holds that the components of any system or systems mutually influence each other and that the organization of a system's behavior is the result of natural laws and constraints, and emerges without an inside agent controlling it (Kelso, 1995). This self-organizing behavior often results in the synchrony or coordination of the system's components. With respect to the coordination of behavioral rhythms, this dynamical systems approach has been effectively used to understand the self-organized synchronization of many different biological systems, from the flashing of fireflies (Hanson, 1978) and chirping of crickets (Walker, 1969) to intrapersonal human interlimb coordination (i.e. bimanual coordination of the finger, leg or arm movements of a single individual) (e.g., Kelso, 1995; Turvey, Rosenblum, Schmidt, & Kugler, 1986). Pertinent to this study, this behavioral coordination has been well demonstrated in the interpersonal movement coordination that occurs both intentionally and unintentionally between two individuals or an individual and an environmental stimulus (Richardson, Marsh, & Schmidt, 2005; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Schmidt, Christianson, Carello, & Baron, 1994; Schmidt & O'Brien, 1997; Schmidt, Richardson, Arsenault, & Galantucci, 2007).

For all the above systems (as well as many more) the patterning of the coordination that occurs is known to be governed by the self-organized entrainment processes of coupled oscillators. More specifically, the coordinated behavior of two

rhythmic limb or body movements is consistent with the dynamics of coupled limit-cycle oscillators. Thus, for 1:1 frequency locked coordination, the dynamic stabilities of such coordination can be captured using a motion equation for the collective variable of relative phase $\phi = (\theta_L - \theta_R)$, the difference in the phase angles of the left and right movements/oscillators. Typically, this motion equation, known as the Haken-Kelso-Bunz (HKB) equation, takes the following form:

$$\dot{\phi} = \Delta\omega - a \sin \phi - 2b \sin 2\phi + \sqrt{Q}\zeta_t, \quad (1)$$

Here, coordination is measured using the change in relative phase ($\dot{\phi}$) as the order parameter—the unit of measure that specifies the spatial temporal order of the rhythmic units. The control parameters—the variables influencing the stability of coordination—are captured by the difference in eigenfrequency between the two rhythmic units ($\Delta\omega$), the coordination strength expressed in the coupling function ($a \sin \phi - 2b \sin 2\phi$), and a Gaussian white noise process (ζ) dictating a stochastic force of strength (Q).

Essentially, the smaller the differences in the eigenfrequencies of the two movements, the larger coupling strength, and the smaller the level of noise present in the system, the stronger and more stable the resulting coordination (Kelso, 1995; Schmidt & Richardson, 2008).

The states of coordination that occur for human interlimb and interpersonal coordination and that are modeled by Equation 1 are referred to as inphase and antiphase. Inphase coordination occurs at a relative phase angle between the coordinating

components of 0° . In this symmetric or congruent phase mode, components are at the same point in their cycles at the same time. Antiphase coordination occurs at a relative phase angle between coordinating components of 180° , and in this alternate or incongruent phase mode, the components are at opposite points in their cycles at the same time (Kelso et al., 1986; Stafford & Barnswell, 1985; Von Holst, 1939/1973). Although both inphase and antiphase are stable states of coordination, the stability of the two phase modes is not equal. A non-linear phase transition from antiphase to inphase coordination occurs when the frequency or tempo of movement (captured by the ratio of the parameters a and b in Equation 1) is increased (Kelso & Scholz, 1985; Hoyt & Taylor, 1981; Gilmore, 1981; Haken, 1977/1983). No such transition occurs from inphase to antiphase. Accordingly, antiphase coordination is known to be intrinsically less stable than inphase coordination.

In addition to the transition from antiphase to inphase at increased frequencies of movement, the difference in the inherent stability of inphase and antiphase coordination is evidenced by the variability of antiphase coordination (as measured by the standard deviation of relative phase ($SD\phi$)) being much greater than the variability of inphase coordination (Kelso et al., 1986). This variability is a result of the noise that is inherent to all movement systems (and all natural systems) and which continuously perturbs movement systems away from the stable states of coordination. Because antiphase is a weaker mode of coordination than inphase, the magnitude of these perturbations and thus the variability of the coordination, is much greater for antiphase compared to inphase. From a dynamical systems perspective movement noise or variability is not necessarily

negative or detrimental to movement coordination and action, and can even have an amplifying or resonating effect on coordination signals (Kelso, 1995; Riley & Turvey, 2002; Schmidt & Richardson, 2008).

The present study

The present study aimed to demonstrate how the differing influences of biological and non-biological movement of human movement variability and coordination are better explained by dynamic systems theory (and the self-organizing entrainment processes of coupled oscillators) than by the mirror systems theory. Two experiments were conducted and employed a similar methodology to that developed by Kilner et al (2003). In both experiments, participants observed a confederate or robotic computer stimulus producing either horizontal or vertical arms movements while producing congruent or incongruent horizontal or vertical arms movements. In Experiment 1, participants were instructed to intentionally coordinate their movements with the confederate or computer stimulus. In Experiment 2, the influence of observing biological and non-biological movements on the participant's movement variability during unintentional coordination was examined by not instructing participants to coordinate with the confederate or biological stimulus. In addition to measuring the end-point variability of the movements (as done by Kilner et al., 2003), the stability and variability of the coordination that occurred between the participant and confederate or between the participant and computer stimulus was also measure. Furthermore, whereas Kilner et al. (2003) only examined the influence of observed human and robotic arm movements, both experiments included a biological-

computer stimulus condition, in which the motion of the computer stimulus was the pre-recorded motion of the confederate, as well as the confederate and computer (robotic) stimulus conditions.

The congruent and incongruent modes are analogous to the inphase and antiphase modes of coordination defined above. Accordingly, incongruent coordination is expected to be weaker than congruent coordination (Kelso et al., 1987, Stafford & Barnswell, 1985; Von Holst, 1939/1973), with greater movement and coordination variability in the incongruent conditions compared to congruent conditions. Additionally, the increased variability witnessed by Kilner during the purely biological trials and not the robotic trials could be due to biological motion's natural variability. This variability in the incongruent confederate trials is not a result of interference in mirror neuron representation, but an attraction towards the more stable, congruent form of coordination. A difference in coordination is expected for the biological and nonbiological conditions, because of the greater strength of bidirectional coupling between biological systems compared to the weaker unidirectional coupling between a biological system and an environmental stimulus. Finally, a similar pattern of coordination across the biological and computer conditions is expected, especially for the unintentional coordination in Experiment 2.

Experiment 1

Experiment 1 attempted to a) replicate the variability findings of Kilner et al. (2003) and b) investigate whether the differences in the variability between biological congruent and incongruent movements were byproducts of the stabilities of the

coordination. A derivative of the method devised by Kilner's et al. was employed, with participants intentionally coordinating horizontal and vertical congruent and incongruent arm movements with the arm movements of a confederate, a robotic image with computer generated movement, and a robotic image reproducing a pre-recorded human movement.

Method

Participants

Seven undergraduate students at Colby College participated in the experiment and received partial course credit for an introductory psychology course or monetary reimbursement. All participants had full use of their limbs and normal or corrected-to-normal vision.

Tasks and Materials

Participants completed fourteen 30 s trials. The trials included one control and three experimental conditions, during which the participant either moved their arm (held straight, with all fingers pointing straight out) horizontally or vertically about the shoulder.

The first experimental condition—the confederate condition— required participants perform arm movements with a confederate. The confederate faced the participant, index fingers 70 cm apart when their arms were fully extended in front of their chest. The confederate swung their arm in time with a 0.5 Hz metronome beat presented to them through headphones. The participant was not presented with a

metronome beat and couldn't hear the metronome beats presented to the confederate. Instead, participants were told to synchronize their movements with the confederate's movements. In two of the four trials the participant and confederate performed congruent movements. That is, the confederate and the participant synchronized their arms horizontally or vertically inphase, such that their arm movements were in the same place in time during the movement's cycle. In the other two trials, the participant and confederate performed incongruent movements. That is, the participant synchronized their horizontal arm movements with the confederate's vertical arm movements, or their vertical arm movements with the confederate's horizontal arm movements. For incongruent coordination, inphase synchronization was defined as being in the top most position of the cycle for the vertical movement when the horizontal movement was in the right most position of its cycle.

In the second experimental condition—the non-biological stimulus condition—the participant stood facing the projection screen, with their arm fully extended, such that their index finger was 70 cm from the projection screen. Participants were instructed to coordinate their movements with the computer generated block figure presented on the projection screen. The block figure stimulus was in the shape of a robot-human (see Figure 1) and swung its right arm about the shoulder either vertically or horizontally at a rate of 0.5 Hz. The arm motion of the stimulus was sinusoidal and computer generated. As in the previous condition, the participant synchronized their movements with the block figure stimulus under congruent and incongruent conditions.

In the third experimental condition—the biological stimulus condition—the participant stood with their arm fully extended (index finger 70 cm from the projection screen) and again were instructed to coordinate their movements with the block figure stimulus. In contrast with the non-biological condition, the arm motion of the block figure was the pre-recorded motion of the confederate swinging at a rate of 0.5 Hz. The participant was not informed the block figure's movement was biological. As in the previous two conditions, the participant synchronized their movements with the block figure stimulus under congruent and incongruent conditions.

The control condition consisted of two trials and provided a baseline recording of the participant's arm movements. Participants were instructed to move their right arm horizontally for one trial, and then vertically for one trial. They began the trial moving in time with a metronome set at 0.5Hz. The metronome was stopped after the first 10 seconds of the trial. While doing this they stood with the index finger of their fully extended arm 70 cm from a blank projection screen, which they were instructed to look at for the entire length of the trial.

Movement about the shoulder was measured using the Liberty 8 magnetic motion tracking system (Polhemus, Ltd) sampling at 120 Hz. One sensor was fixed to the tip of the index finger of both the participant and the confederate. A Dell XPS Core Duo 2 PC computer was used to record the movement times of the participant and present the stimulus figure on the projector screen.

Procedure

Participants were told that the purpose of the experiment was to investigate the control of arm movements. After signing the consent form, they were instructed on how to perform the required arm movements. They were told to make vertical and horizontal sinusoidal arm movements about the shoulder, keeping their arm straight and their fingers pointing directly ahead of them. Participants practiced until they could perform the movements proficiently.

Each participant completed all four conditions, starting with the baseline condition, and followed by three experimental conditions. The order of the three experimental conditions was counterbalanced across participants. The order of the congruent and incongruent trials within each condition was also counterbalanced.

After completing all conditions, the participants were asked what they thought the experiment was investigating and then debriefed.

Design and analysis

The experiment was a 2(movement direction: vertical, horizontal) \times 2(congruency: congruent, incongruent) \times 3(condition: confederate, biological stimulus, non-biological stimulus) within-subjects design. All of the motion time series for each trial were centered around zero and low-pass filtered with a cut off frequency of 5 Hz using a Butterworth filter.

To determine the stability and accuracy with which the participants and confederate produced the specified period of movement, the mean period and SD of period were calculated for each trial as the time between the points of maximum angular

extension as defined by the peaks of the specified (dominated; either horizontal or vertical) movement time series.

In replication of Kilner et al. (2003), the degree to which the participant's arm movements were influenced by the observed movements was determined by calculating the end-point variance of the participant's arm movements orthogonal to the dominant dimension of movement. For example, if the participant was making movements in the X (left-right) dimension, variance was calculated in the Z (up-down) dimension. Similarly, if the subject was making movements in the Z (up-down) dimension, variance was calculated in the X (right-left) dimension.

To determine the degree and strength of coordination that occurred between the participant's arm movements and the movements of the stimulus or the confederate, the deviation from intended phase—as defined above—and the standard deviation of relative phase ($SD\phi$) was calculated for each trial. To calculate this, the motion time series for the dominate dimension of the participant's and confederate's and/or computer stimulus's movements (depending on condition) were differentiated to obtain two velocity time series. These velocity time series were then normalized by angular frequency and the movement phase angles (θ deg) calculated for each arm as

$$\theta_i = \arctan(\dot{x}_i / x_i), \quad (2)$$

where \dot{x}_i is the normalized angular velocity at the i th sample (normalized in terms of the mean angular frequency for the trial) and x_i is the angular displacement of the i th sample. The difference between the phase angles of the two arm movements were computed ($\phi = \theta_{Ch1} - \theta_{Ch2}$), and the deviation from indented phase (mean relative phase minus intended

relative phase; $M\phi - \Psi\phi$) and $SD\phi$ were calculated from the resulting relative phase time series.

Results

There were no effects for movement direction so the data was collapsed across this factor. Each dependent measure was thus analyzed using 2(congruency: congruent, incongruent) \times 3(condition: confederate, biological stimulus, non-biological stimulus) repeated measures ANOVA. The data from one participant was dropped from the analysis due to a hardware (sampling) malfunction that resulted in lost motion data.

Period

The mean period and SD of period of the participant and the confederate's arm movements were analyzed to verify that the participant and confederate produced the movements at the target frequency (0.5 Hz). The analysis of both mean period and SD of period revealed no significant effects (all $p > .12$). The participants produced a mean period of 1.99 s (SD = .06 s) and 1.93s (SD .10 s) for the congruent and incongruent conditions, respectively. The confederate produced a mean period of 2.00 s (SD = .06 s) and 1.99 s (SD .07 s) for the congruent and incongruent conditions, respectively.

Variance

In contrast to the findings of Kilner et al. (2003), the analysis of end-point variance revealed no significant effect for condition, $F(2, 7) < 1, p > .05$, or congruency, $F(1, 7) < 1, p > .05$, nor was there any condition by congruency interaction, $F(2, 7) < 1, p > .05$. As can be seen from Figure 2 the biological incongruent movement condition did

not illicit significantly more variability than the biological congruent condition or any of the robotic conditions.

Relative Phase

The analysis of the deviation of relative phase revealed a significant main effect for condition $F(2, 7) = 8.25, p < .01$, a significant main effect for congruency, $F(1, 7) = 10.02, p < .02$, and a significant condition x congruency interaction $F(2, 7) = 5.45, p < .05$ (see Figure 3). Participants exhibited a phase lead when coordinating with the confederate and a phase lag when coordinating with the computer stimulus. In addition, the magnitude of this phase lag for the computer stimulus conditions was greater for the incongruent compared to the congruent trials.

The analysis of the standard deviation of relative revealed a significant main effect for condition $F(2, 7) = 4.22, p < .05$, with the coordination being more stable for the biological condition than for both of the computer stimulus conditions (see Figure 4). There was also a significant main effect for congruency $F(1, 7) = 23.60, p < .01$, with coordination in congruent conditions being more stable (less variable) than the coordination in the incongruent conditions. There was no interaction between condition and congruency, $F(2, 7) < 1, p > .05$.

Discussion

The primary focus of Experiment 1 was to replicate the variability findings of Kilner et al. (2003). Kilner found increased variability for the biological incongruent condition, and virtually the same level of variability for all other conditions (baseline, biological congruent, robotic congruent, and robotic incongruent). The

current experiment did not replicate this finding, showing no significant differences between any conditions or congruencies. This suggests that for intentional coordination, subject's movements were not affected by different types of movement (congruency) or movement made by different systems (condition). According to mirror systems theory, interference should have been far greater for the biological incongruent condition compared to all other conditions, but our findings suggest no difference in interference for any of the conditions. Although it is difficult to determine why Kilner's results were not replicated, one possible influence is that the robotic movement in Experiment 1 was sinusoidal, which was not the case in Kilner's study. Sinusoidal movement better resembles biological movement, eliciting more stable coordination and thus less variability (Press, Bird, Flach, & Heyes, 2005). Regardless, their explanation for the influence of incongruent movement on perception and action does not hold for this set of data, because the mirror systems theory posits a completely separate neural representation for robotic motion. The variability findings can only be explained by the dynamic systems theory which suggests that intentional coordination is a strong and stable coupler that will assist in motion consistency in all types of conditions, including non-biological conditions.

Experiment 1 also investigated whether the difference in variability Kilner observed between biological congruent and biological incongruent motion was due to different coordination strengths between the two types of movement. Although the variability difference Kilner found between these conditions was not replicated, Experiment 1 found that incongruent coordination has weaker attractor strength. For all

conditions (confederate, biological stimulus, and nonbiological stimulus), congruent coordination showed significantly less standard deviation from relative phase than incongruent coordination, exemplifying stronger (more stable) coordination. Dynamic systems theory explains this difference as a difference in attractor states. It appears that much like inphase has stronger coordination than antiphase, congruent motion has stronger coordination than incongruent motion.

Results revealed that biological motion elicits significantly stronger coordination than either type of robotic motion. Both congruent and incongruent confederate trials had lower standard deviations of relative phase than any of the biological stimulus and nonbiological stimulus trials. Even though there was no significant evidence that the confederate significantly changed her motion to match that of the participants, this does not rule out the possibility that an immeasurable amount of bidirectional coupling occurred. Dynamic systems literature and studies support this assumption (Kelso 1995; Schmidt & Richardson, 2008). The bidirectional nature of the confederate coordination, along with the system's natural noise, increases the strength of coordination. This increase would not be found with the unidirectional coupling existing between the participant and both robotic conditions. Yet, as dynamic systems theory would predict, coordination was still observed for both robotic conditions, despite both of them being unidirectional and one of them lacking natural movement noise.

Results for deviation from intended relative phase revealed that, generally, participants exhibited phase lead when coordinating with a confederate and phase lag when coordinating with the computer stimulus. Participants led the confederate's

motion, and followed the computer's motion. This may also be a result of the bidirectional nature of the confederate trials. Because of this bidirectionality, participants could assume that the confederate could follow their motion, yet the robotic motion could not. Additionally, phase lag was greater for incongruent motion in the robotic trials, which is further evidence that this movement pattern is inherently less stable. A post hoc analysis on these results revealed that none of the phase lags or leads were significantly different than zero ($P > .13$), suggesting that the original significance finding were due to the negative values of confederate trials and the positive values of both robotic trials. Thus although a clear trend is observed, it is not significant.

Experiment 2

Although the results of Experiment 1 demonstrate that more stable coordination occurred for biological motion and congruent motion, the question as to whether unintentional coordination will elicit the same effect remains. Experiment 2 investigated the influence of observed biological and non-biological movements using an unintentional coordination paradigm. Coordination is expected to be weaker, and variability greater for unintentional coordination but the same trend seen for intentional coordination should be observed. Additionally, if coordination is found in the computer stimulus condition, it will lend further support to the dynamic systems explanation of these coordination phenomena.

Method

Participants

Eight undergraduate students from Colby College participated in the experiment and were monetarily reimbursed (US \$10) for their participation. All participants had full use of their limbs and normal or corrected-to-normal vision.

Tasks and Materials

The same tasks and materials used in Experiment 1 were employed for the current experiment. Participants completed the same 14 conditions except they were not instructed to coordinate. While performing each trial, participants looked at two puzzle images with numerous minor differences, and verbally recited the differences as they found them (see Figure 5). The pictures were held at chest height by the confederate and pasted on the chest of the block figure stimulus. This task was meant to disguise the real purpose of the study (measuring coordination and variability of movement), and to assure that participants still visually attended to the confederate and/or block figure stimulus (Richardson et al., 2005). The trials were 45 seconds, instead of 30 seconds as in the Experiment 1, in order to provide adequate time for the puzzle task. To ensure that participants produced movement at the target tempo of 0.5 Hz, participants began swinging their arms in time to a metronome beat for 5 s before the trial began, after which the metronome was shut off for the trial and participants were instructed to try to maintain the same pace throughout the rest of the trial.

Procedure

Participants were told that the purpose of the experiment was to investigate the effect of performing and observing distracting limb movements on problem solving. After signing the consent form, they were instructed on performing the required arm

movements. They were told to make vertical and horizontal sinusoidal arm movements about the shoulder. Participants practiced until they were proficient. During the experimental trials, the metronome was not played, except for the first ten seconds of the control trials. Following this they were instructed on performing the puzzle task. They were told to look for the differences between two images presented during each 45 second trial and verbally point out each difference as they found it.

Participants were run in the four different conditions, starting with the baseline conditions, and followed by the remaining three experimental conditions. The order of the three experimental conditions was counterbalanced across participants. The order of the congruent and incongruent trials within each condition was also counterbalanced.

Upon completing all conditions, the participants were asked what they thought the experiment was investigating and then debriefed.

Design and analysis

The experiment was a 2(movement direction: vertical, horizontal) \times 2(congruency: congruent, incongruent) \times 3(condition: confederate, biological stimulus, non-biological stimulus) within-subjects design. All of the motion time series for each trial were centered around zero and low-pass filtered with a cut off frequency of 5 Hz using a Butterworth filter.

As in experiment 1, we determined the stability and accuracy with which the participants and confederate produced the specified period of movement by calculating the mean period and SD of period for each trial. Similarly, the degree to which the participant's arm movements were influenced by the observed movements was

determined by calculating the end-point variance of the participant's arm movements orthogonal to the dominant dimension of movement.

To determine the degree of unintentional coordination that occurred between the participant's arm movements and the movements of the stimulus or confederate, the distribution of the relative phase angles was calculated for each trial. Recall, that the greater the concentration of phase angles at or near 0° or 180° , the stronger (more stable) the coordination. The difference between the relative phase angles of the two arm movements were computed ($\phi = \theta_{Ch1} - \theta_{Ch2}$)—see Experiment 1 for how relative phase angles were calculated—and the percentage of relative phase angles that occurred across the 9 different relative phase regions (i.e., $0-20^\circ$, $21-40^\circ$, ..., $161-180^\circ$) was determined.

Results

Period

The mean period of motion for both the participant and the confederate were analyzed to investigate whether the subject maintained the intended period and whether the confederate was affected by the motion of the subject. No significant effect was found for condition, congruency, or the Condition \times Congruency interaction for the period and standard deviation of period for the participant ($p > .29$). The participants produced a mean period of 1.89 s (SD = .11 s) and 1.90 s (SD = .11 s) for the congruent and incongruent conditions, respectively. The confederate produced a mean period of 2.01 s (SD = .07 s) and 2.02 s (SD .06 s) for congruent and incongruent conditions, respectively.

Variance

The analysis of the end-point variance revealed a significant effect for condition, $F(2, 8) = 4.79, p < .02$. As can be seen from Figure 6, there was less variance for both congruent and incongruent biological conditions than for any of the robotic conditions and the baseline conditions. There was also a marginal effect for congruency, $F(1, 8) = 4.32, p < .08$, with more variability for congruent trials than for incongruent trials. There was no Condition \times Congruency interaction $F(2, 8) < 1, p > .05$.

Distribution of Relative Phase

The analysis of the distribution of relative phase revealed a significant effect of phase region, $F(8,8) = 2.74, p < .02$ and a significant three-way interaction between, condition, congruency and phase region, $F(16,8) = 2.16, p < .02$. As can be seen from Figure 7, the participants became unintentionally coordinated with the movements of the confederate and with the movements of the computer-stimulus in both the computer-biological and computer non-biological conditions. Unintentional coordination was also observed for both the congruent and incongruent trials, and although there appears to be more antiphase coordination for the confederate incongruent and biological stimulus incongruent conditions, this difference was viewed as trivial due to the arbitrary definitions of inphase and antiphase for the incongruent trials (because they are on different spatial frames of reference, there is no definite 0° or 180° phase relation).

Discussion

Unlike Experiment 1, Experiment 2 found significant differences between the variability of conditions and congruencies. Variability was higher for incongruent motion in all conditions, further suggesting that incongruent motion is an inherently less stable

movement pattern than congruent motion. Both types of biological motion had significantly less variability than any other condition, including the baseline condition, suggesting that the bidirectional coupling had an even greater influence on unintentional coordination than on intentional coordination. Thus biological motion elicits more stable movement coordination patterns because it has a greater coupling strength than any type of robotic motion.

The synchrony findings from Experiment 2 further support a dynamic systems explanation of the mutual influences of perception and action. As dynamic systems theory would predict, coordination was found in all conditions and congruencies. Mirror systems theory would not predict unintentional coordination (or imitation) for any of the robotic conditions—because robotic motions are represented in different neural locations—whereas dynamic systems theory predicts that a system will become entrained with any environmental system as long as adequate coupling exists and the difference in maintenance frequencies between the systems is not greater than the strength of the coupling. Not only was coordination observed for all conditions, but the amount of coordination was similar, further suggesting a dynamic systems explanation of the phenomena. We did not find any significant differences between the conditions or congruencies. Although the previous results suggest that the bidirectional coupling that occurred in the confederate trials should have caused greater coordination for this condition, and the weaker attractor for incongruent motion should have caused less coordination for all incongruent trials, dynamic systems theory explains why this was not found. Unintentional coordination is naturally weaker than intentional coordination, and

thus does not elicit as robust findings. Because of this, an increase in the control parameter ($\Delta\omega$) is often necessary to test coordination stability (Schmidt & Richardson, 2008). The frequency of arm movements in this experiment (0.5Hz) wasn't fast enough to sufficiently test the inherent stability of the two movement patterns. Thus future experiments should examine whether an increase in the frequency, or frequency detuning, demonstrate congruent coordination to be a more stable pattern of coordination than incongruent coordination, exhibiting a bifurcation pattern that one would predict based on the standard deviation of relative phase data from Experiment 1 and the variability data in Experiment 2.

Conclusions

The results of Experiment 1 and Experiment 2 are better explained by the dynamic systems theory than the mirror systems theory. The observed relationship between perception and action, and how this relationship resulted in interpersonal coordination, can only be fully explained by the dynamic systems theory.

Experiment 1 did not find any variability differences indicative of mirror neuron interference. The strong coordination and weak variability witnessed in this first experiment demonstrate a stable coupling occurring between two intentionally coordinated systems, as explained by the coupled oscillator dynamic and dynamic systems theory. Also explained by the coupled oscillator dynamic is the greater stability of biological coordination, because it has an inherently stronger coupling as a result of its bidirectional nature. Finally, the first experiment showed incongruent coordination to be

less stable than congruent coordination for all conditions, which could cause greater variability.

Experiment 2 found unintentional biological motion to be more stably coordinated (less variable), which is best explained by the self-organized coupled oscillator dynamic because of its stronger bidirectional coupling. Incongruent motion was more variable across all trials, adding evidence to the argument that it is an inherently weaker movement coordination state. Finally, coordination was observed across all conditions, a phenomenon dynamic systems theory would predict, but which mirror systems theory can not explain in the robotic trials, because of its emphasis on neural representations.

None of this is to say that mirror neurons do not exist, or that they do not have an effect on action and perception, including imitation and interference, but mirror systems theory is not a complete explanation of the observed phenomena. It can only explain certain aspects of movement coordination (biological coordination), but can not explain entrainment with environmental stimuli. It is also unable to explain the weaker coordination observed for all types of incongruent motion. Dynamic systems theory more completely explains these phenomena (among many others). Mirror systems theory is not a complete explanation. Instead, mirror neurons appear to be just another level at which coordination as explained by the dynamic systems theory presents itself. Not only do self-organized coordinating behaviors governed by the coupled oscillator dynamic occur in firefly flashing, cricket chirping, between limbs, and between people, but they also occur between neurons in the STS.

Future research should focus on variability in intentional coordination, to further examine why the results of Experiment 1 and the results of the study conducted by Kilner et al. (2003) did not agree. A study investigating variability with two conditions of robotic motion, one with sinusoidal motion and one without, would test whether the theory presented in this paper accurately explains the failure to replicate Kilner's findings. If it did, it would lend further support to dynamic systems theory, by eschewing the idea of robotic motion being represented in a completely different location, and by adding evidence to the theory that the more nonbiological motion resembles biological motion, the greater coordination is (Press, Bird, Flach & Heyes, 2005).

Future research should also further test the hypothesis that incongruent motion is inherently weaker attractor than congruent motion. One way to examine this would be to rerun the unintentional coordination experiment increasing either the frequency or the frequency detuning to see whether a nonlinear bifurcation transition, as observed in antiphase and inphase motion, occurred for incongruent and congruent motion.

The current experiment provides evidence for a dynamical systems explanation of the relationship between perception and action and the results of this relationship, including those results explained by the mirror systems theory.

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Figure Captions

Figure 1. Block figure stimulus used for the biological and non-biological stimulus conditions.

Figure 2. Non-significant variance across all conditions for Experiment 1.

Figure 3. Deviation from relative phase across all conditions for Experiment 1.

Figure 4. SD of relative phase across all conditions for Experiment 1.

Figure 5. Two puzzle image examples.

Figure 6. Variance across all conditions for Experiment 2.

Figure 7. a. Distribution of relative phase for the confederate condition for Experiment 2.

b. Distribution of relative phase for the biological stimulus condition for Experiment 2.

c. Distribution of relative phase for the non-biological stimulus condition for Experiment 2.

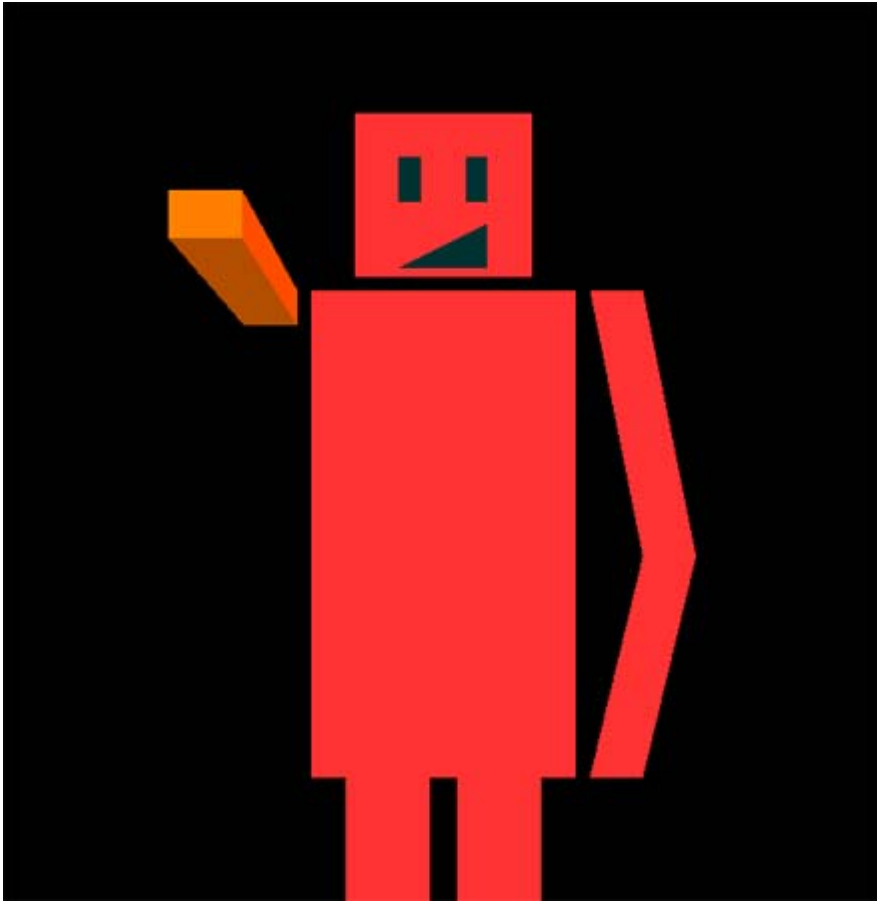


Figure 1.

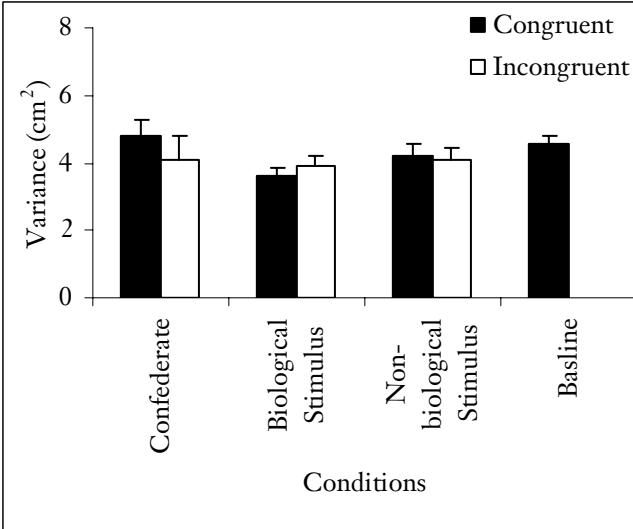


Figure 2.

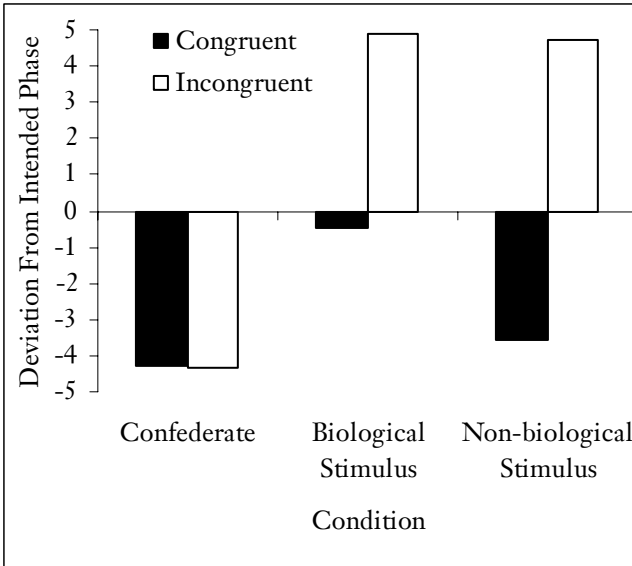


Figure 3.

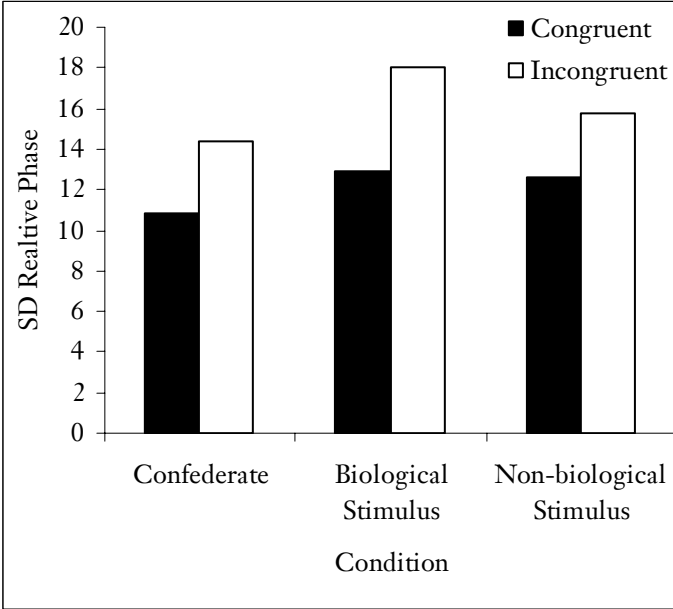


Figure 4.

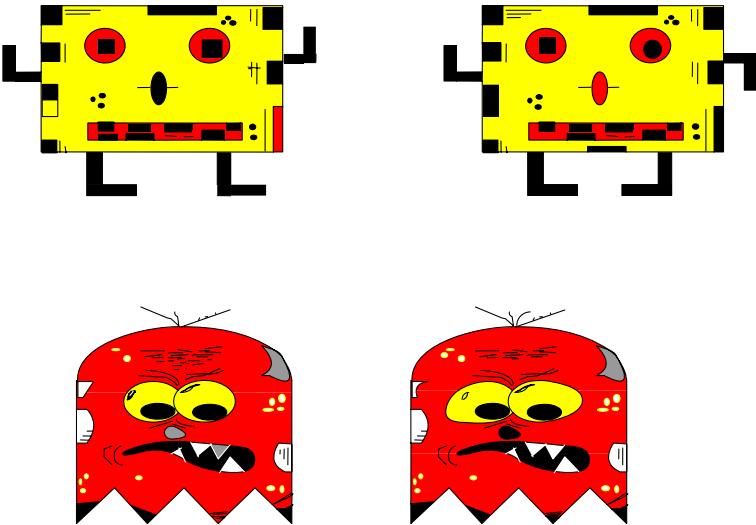


Figure 5.

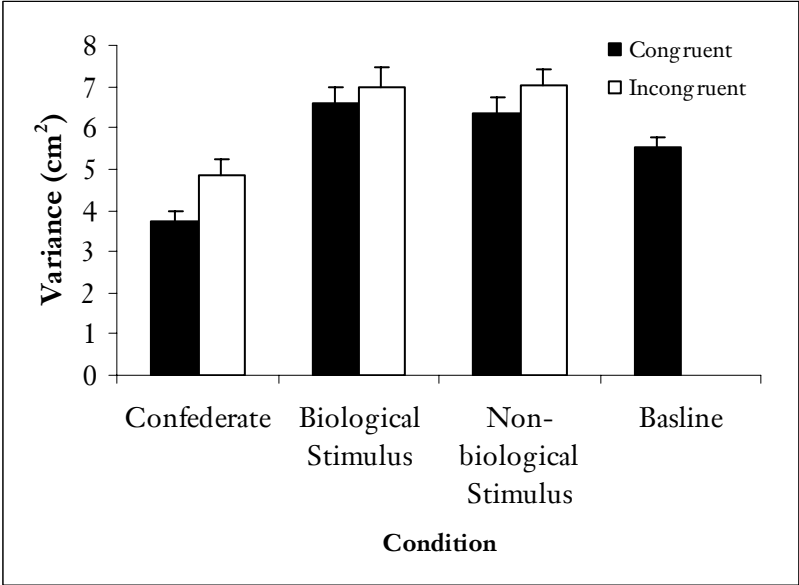


Figure 6.

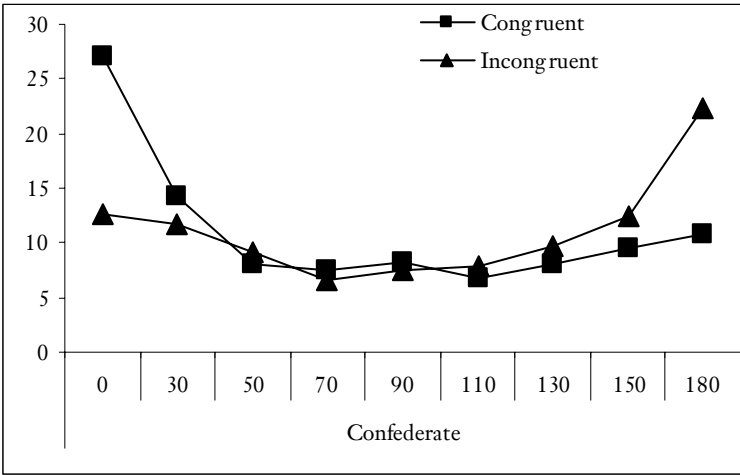


Figure 7a.

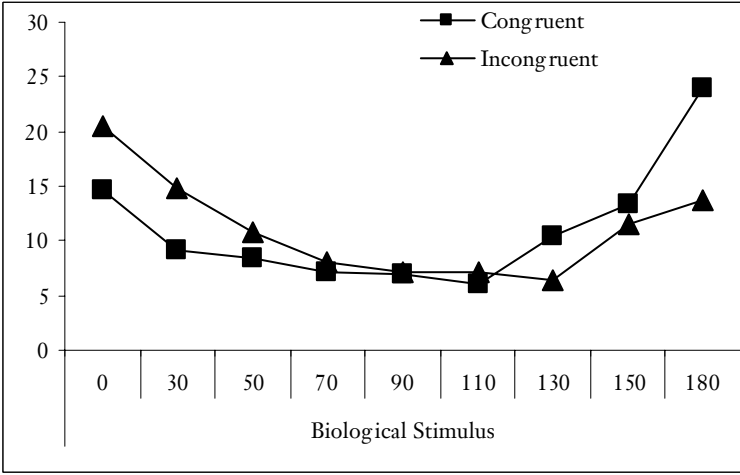


Figure 7b.

Effect of Observed Biological and Non-biological Movement 45

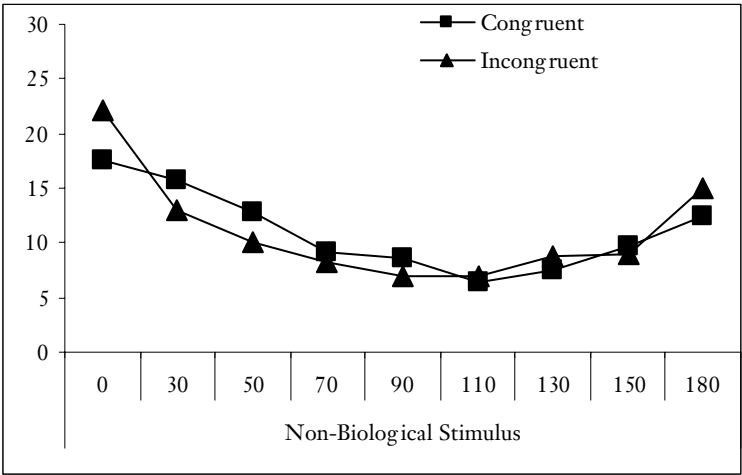


Figure 7c.