Symmetry Building and Symmetry Breaking in Synchronized Movement

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Abstract

Mirror symmetry between individuals is a behavioral phenomenon that is commonly observed in conversation: individuals tend to mimic each other's postures and gestures as a part of a shared dialog. The present work studies the process of symmetry building and symmetry breaking in the movements of pairs of individuals while imitating each others' movements in dance. Spatial and temporal symmetries are found in the overall velocities from the results of full body motion tracking.

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Introduction

Symmetry has many forms and has been shown to be a powerful organizing mechanism in perception (Bertamini, Friedenberg, & Kubovy, 1997; Kubovy, 1994; Palmer & Hemenway, 1978). Types of *spatial symmetry* in natural objects include the bilateral symmetry of most multicelled animals, other classes of repeating patterns exemplified by the symmetry classes of crystalline structures (Senechal, 1990), and algorithmic symmetry found in plants (Lindenmayer & Prusinkiewicz, 1990). In general, spatial symmetry can be considered to be a form of self–similarity across spatial intervals. When two objects exhibit bilateral symmetry that occurs about a plane between them, then they exhibit *mirror symmetry.* That is, the objects are spatially translated on one axis and flipped about another axis exactly as is one's image in a mirror.

The same logic can be applied to temporal structures. *Temporal symmetry* is considered to be a form of self–similarity over intervals of time. Thus, a simple repeating auditory rhythm such as would be produced by a drum machine can be considered to have a form of symmetry called *translational symmetry.* In this case the rhythm is repeated, thus it is self–similar across time. The symmetry in this case involves translation in time, but no mirror–flip. Temporal symmetry provides organizational structure that is perceived as a Gestalt.

If a person makes a gesture with the left hand and then makes the same gesture with the right hand, then we could say the person exhibits *spatiotemporal symmetry.* Both spatial bilateral symmetry and temporal symmetry were involved in the production of these coordinated gestures. Similarly, if two people face each other and one makes a movement with the right arm and the other person then mimics that movement with her or his left arm, then this dyad exhibited spatiotemporal mirror symmetry. We will explore spatiotemporal mirror symmetry in dyads as one person mimics another while they stand face to face.

Symmetry Formation in Conversation

There are many features of conversational behavior that give rise to symmetry. The most striking of these, obvious to even the casual observer, is that people tend to mimic each other's posture during conversation (Lafrance, 1985). This mirror symmetry in conversants' posture and gesture is not complete. In fact, if one conversant mimics her or his conversational partner too closely this will almost always be immediately noticed by the partner and can become a source of discomfort and embarrassment for the partner being mimicked.

What communicative purpose does this mirror symmetry in posture and gesture serve during conversation? One possible explanation is that by creating mirror symmetry a conversant is attempting to physically access the somatosensory inner state of his or her interlocutor. To the extent that cognitive or emotional states are correlated with physical postures, gestures and facial expressions, one may be able to trigger the experience of an internal state by placing one's body in a particular position, making a particular gesture or expression. Thus, one might expect that the formation of symmetry in conversation might signify common internal states and thus facilitate communication (Bavelas, Black, Chovil, Lemery, & Mullett, 1988).

A second possible explanation is that by forming symmetry with an interlocutor a conversant is attempting to express agreement or empathy. This explanation is fully congruent with the first explanation since it is predicated on the idea that the conversant has information leading him or her to believe that creating symmetry will be understood by the interlocutor as conveying that the conversant is experiencing or has knowledge of a similar inner state as is being experienced by the interlocutor.

The second explanation does not account for the phenomenon of embarrassment caused by excessive symmetry. However, if symmetry formation is a communicative strategy for understanding, when a conversant forms too much symmetry with her or his interlocutor, it might signal too much access to the interlocutor's inner state causing an embarrassing sense of loss of privacy.

Symmetry Breaking in Conversation

As symmetry is formed between two conversants, the ability of a third party observer to predict the actions of one conversant based on the actions of the other increases. In this way we can consider there to be an increased redundancy in the movements of two conversants as the symmetry between them increases. Formally, the opposite of redundancy is information as proposed by Shannon and others (Redlich, 1993; Shannon & Weaver, 1949). Thus, when symmetry is broken, the third party observer of a conversation's postures and gestures would be surprised. The observer's previously good predictions would now be much less accurate. In this way we can consider the breaking of symmetry as a method for increasing the nonverbal information communicated in a conversation.

We consider the interplay between symmetry formation and symmetry breaking in posture and gesture to be integral to the process of communication. The spatiotemporal structure of the formation and breaking of symmetry is likely to be diagnostic of a variety of social and cognitive aspects of the dyadic relationship. This diagnostic should be relatively insensitive to the semantic content of the conversation, but instead will express the large scale interpersonal prosodic nature of the dyadic interaction.

Perception–Action Loops and Mirror Systems

Mirror systems as studied by Rizzolati and colleagues (Rizzolatti & Arbib, 1998) are hypothesized to provide a link between the integration of the perception of an individual's self–movement and the perception of another individual's mirrored movement. In macaques, it has been found that the same neuron will fire when a particular movement is made by the monkey or when the monkey observes the same movement made by a researcher. Since there exists a class of these mirror neurons that (a) fires only in the presence of a movement that includes an actor, an action and an object acted upon, and (b) is located in the macaque's brain in an area that is likely to correspond to an area in the human brain implicated in syntax (Broca's area), there has been speculation that such a mirror system may be an evolutionary step on the road to the development of language (Gallese & Goldman, 1998).

Given these assumptions, we wonder: How well might such a mirror system perception–action loop perform in ideal circumstances? Is there a difference between the situation in which both individuals attempt to synchronize with each other as compared with when one person provides a leading stimulus and another follows? What are the time lags that separate leaders and followers when both can hear an external synchronizing stimulus?

An Experiment in Symmetry and Dance

In order to answer the previous questions and to further explore the nature of dyadic perception–action loops, we designed an experiment in which individuals listened to a repeating rhythm and were asked to either lead or follow their partner in a free–form spontaneous dance. During the dance, both participants' movements were tracked and recorded to a computer. Thus, the temporal structure of the symmetry formation and symmetry breaking between the two participants in a dyadic perception–action loop involving the mirror system could be examined.

Participants

Six dyads of young adults were recruited from undergraduate psychology classes at the University of Notre Dame. Each dyad consisted of one male and one female participant. Some participants were previously acquainted and others had not previously met. Data from one dyad was not used since one of the participants in the dyad refused to follow instructions.

Apparatus

An Ascension Technologies MotionStar 16 sensor magnetic motion tracking system was used to track the motions of participants. Eight sensors were placed on each individual: one on a the back of a baseball cap worn tightly on the head, one strapped just below each elbow using a neoprene and velcro around–the-limb strap, one held to the back of the back of each hand with an elastic weightlifting glove, one held to the sternum with a neoprene and velcro vest, and one strapped just below each knee with a neoprene and velcro around–the–limb strap. Each sensor is connected to the MotionStar system computer with a long cable. Thus each individual had a bundle of 8 cables that were gathered and positioned behind them in order to provide the minimum of interference with movement.

Methods

Participants were strapped into the sensors and led into the measurement room where they were instructed to stay within a 1m × 1m square marked with tape on the floor of the room. The two regions were 1.5m apart at their nearest edge. Headphones were worn by each participant and they were then instructed that during each trial they would hear a repeating rhythm lasting approximately

40 seconds during which time they were to dance in synchrony with the rhythm without touching each other. Prior to each trial they would be instructed over the headphones whether to lead or follow their partner during that trial.

Each trial stimulus consisted of a repeating rhythm synthesized by computer to have a beat interval of 200 ms and either 7 or 8 beats per repeating measure. Eight stimuli were chosen from a set of stimuli with known properties of perceived segmentation (Boker & Kubovy, 1998). At the beginning of each trial each person was either instructed to lead or follow. Thus there were four instruction conditions: (1) person A leads and person B follows, (2) person A follows and person B leads, (3) both person A and B lead, and (4) both person A and B follow.

Results

In order to simplify the analysis of the movements, data from the eight sensors attached to each dancer were combined in order to calculate an overall velocity at each sample interval in the following manner. First the sternum sensor position was subtracted from each of the other sensors so that all limb positions and the head position were relative to the position of the trunk. Then the velocity along each axis for each sensor was calculated as

$$v_{ij}(t) = \frac{x_{ij}(t+3) - x_{ij}(t-3)}{6(1/80)} \;, \qquad (1)$$

where $v_{ij}(t)$ is the velocity at sample t for sensor i along axis j, and $x_{ij}(t-3)$ is the position in centimeters relative to the trunk at sample $t-3$ for sensor i along axis j. The difference in the two sampled positions is divided by 6(1/80) since there are six intervals between the two samples and each interval is 1/80th of a second. Thus the estimated velocity at each sample time t is effectively low pass filtered to remove high frequency noise and is expressed in units of cm/sec.

Finally the results of all velocity calculations at each time t were combined as a root mean square to give the overall movement of an individual as

$$\bar{v}(t) = \left(\frac{\sum_{i=1}^{8} \sum_{j=1}^{3} v_{ij}(t)^2}{24} \right)^{\frac{1}{2}} . \quad (2)$$

Thus the root mean square velocity $\bar{v}(t)$ gives an estimate of the total activity for a dancer at time t. While this overall estimate of velocity does not give any estimate of the accuracy with which spatial symmetry is formed, it does give an estimate of the overall amount of temporal symmetry when it is analyzed using cross–correlational analysis.

The root mean square velocity was calculated for each trial and was then predicted using a mixed effects model grouping by subject within dyad. Predictor variables in the model were the sex of the subject, the length of the repeating rhythm and the instruction category. There was no significant effect of sex on the overall RMS velocity during the dance. There was an effect of length of the rhythm ($p < 0.01$) such that rhythms with 8 beats per measure produced higher velocities than rhythms of length 7.

Cross–Correlation of Two Dancer's Velocities

In order to gain a summary estimate of the symmetry between dancer's overall velocities, we calculated the lagged cross–correlation of the two dancer's RMS velocities during short intervals of time. For two second windows of time, 160 samples of velocity, we calculated the correlation between the two dancers where the onset of the windows was lagged by values on the interval $-2\text{sec} \leq \tau \leq +2\text{sec}$. Thus a trial resulted in an $T \times I$ matrix of correlations where, for a target time t during the trial, a vector of correlations r_{ti} was calculated as

$$r_{ti} = \left\{ \begin{array}{ll} r((x_t, \ldots, x_{t+w}), (y_{t-j}, \ldots, y_{t-j+w})) & \text{if } j \geq 0 \\ r((x_{t+j}, \ldots, x_{t+j+w}), (y_t, \ldots, y_{t+w})) & \text{if } j < 0 \end{array} \right\} , \quad (3)$$

where the index i is on the integer interval $1 \leq i \leq I$, I is an odd number, $r()$ is the Pearson product moment correlation function, j is a lag index calculated as $j = (i-1) - ((I-1)/2)$, and w is the total number of samples within a window. In the present case, we chose $w = 160$ and $I = 321$ so that given an 80 Hz sampling rate, we correlated 2 second windows lagged by as much as 2 seconds from each other.

A detailed examination of example trials gives an idea of the time course of how the symmetry forms between individuals and how it can be broken. In Figure 1 are plotted matrices of cross–correlations with colors indicating the value of the correlation in each cell. Each row of these graphs plots one target time during 20 seconds of the trial with time since beginning of the trial on the vertical axis. Each column of the graph plots one lag value. A lag of zero is in the column at the center of the horizontal axis, person A is leading for columns to the left of center, and person B is leading for columns to the right of center.

When both participants were instructed to follow, the cross–correlations were likely to appear as in Figure 1–a. A short, five second period of settling of the two participants occurred at the beginning of the trial during which time they each followed the others' movements. Then as they became still and stood and stared at each other, there was no temporal structure to their velocities, which were near zero.

When both participants were instructed to lead, very often temporally symmetric motions would become evident. Even though each was instructed to lead, participants would mutually entrain into spatiotemporal symmetry. An example of this type of behavior can

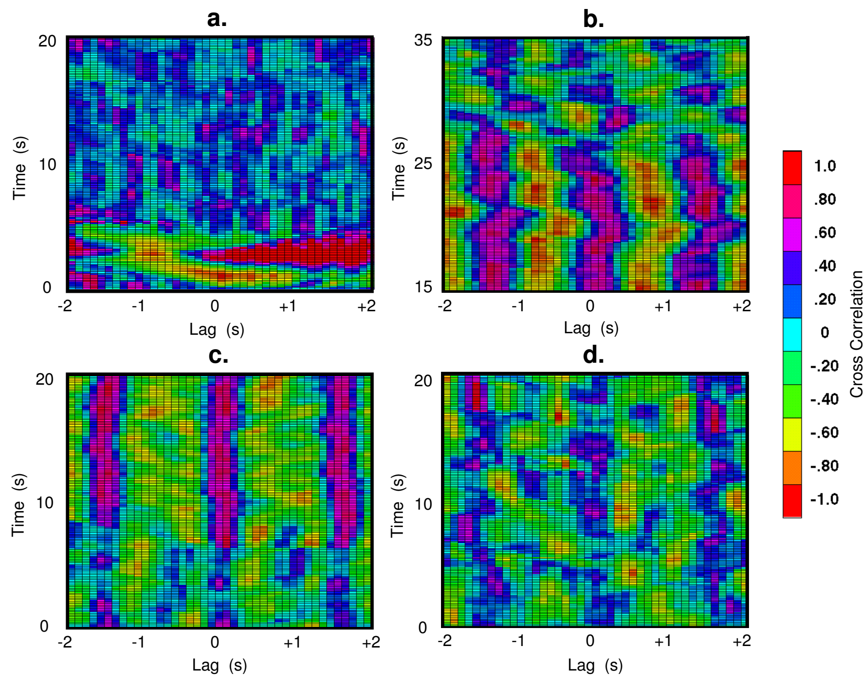

Figure 1. Cross–correlation matrices plotted for twenty seconds from four example trials. The scale on the right denotes the color assigned to each value of cross correlation. (a) The beginning of a trial in which both subjects were instructed to follow. (b) Twenty seconds from the middle of an example trial in which both subjects were instructed to lead. (c–d) The beginning of two example trials in which one subject was instructed to lead and the other to follow.

be seen in Figure 1–b which plots 20 seconds from the middle of a trial in which both participants were instructed to lead. The strong vertical purple bands, which peaks are separated by approximately 1400 ms and occur during the interval 15 seconds to about 27 seconds from the beginning of the trial, indicate the presence of strong spatiotemporal symmetry in the dyad's motions. However, at around 27 seconds there is a breaking of symmetry. It may be that one or the other of the participants became aware that they were following the other and decided to break the symmetry in order to take the lead.

Figure 1–c and 1–d plot example trials in which one dancer was leading and one dancer was following. In Figure 1–c is plotted an example of the quick formation of strong, stable symmetry in a trial as exhibited by the vertical purple bands beginning around 8 seconds into the trial. As a contrast, Figure 1–d plots an example trial at the other end of the spectrum, in which only weak symmetry of motion was established.

Implications for Mirror Systems

The results of the current experiment demonstrate that when individuals coordinate their movements in a lead–follow or lead–lead dance to a repeating rhythm, the overall velocity of each individual entrains reliably with the length of the perceptual segmentation from the auditory stimulus. Thus, cyclic movement is created with a frequency that matches the frequency of the repeating rhythm and stable, reliable, and near zero between–individual phase lags are present. While it may be unremarkable that this situation occurs when one individual is instructed to lead and the other to follow, it is somewhat unexpected that this small phase lag between–individual entrainment occurs when both individuals are instructed to lead. Thus strong spatiotemporal symmetry was observed even when both individuals were instructed to lead: that is to ignore any symmetry that occurred between them.

The strong lead–lead correlation between individuals' velocities, while reliably smaller than that of the lead–follow condition, is so strong that it suggests that entrainment of cyclic movements between individuals may be especially easy. One possible mechanism for this entrainment may be a spatiotemporal component to mirror systems. If this type of entrainment is easier than other forms of mimicry, then this would provide a possible explanation for the near universal use of a cyclic movement of the head to nonverbally indicate agreement or disagreement during conversation. The primary information that needs to be communicated nonverbally by a listener during conversation, understanding or misunderstanding, would be likely communicated by a method that would allow the quickest recognition of entrainment between individuals. If this argument holds, we expect a special bias toward cyclic movement in mirror systems: a bias towards spatial mirror symmetry and temporal translational symmetry.

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