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Journal

Proceedings of the Annual Meeting of the Cognitive Science Society, 37(0)

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Publication Date

2015

Interpersonal Anticipatory Synchronization: The Facilitating Role of Short Visual-Motor Feedback Delays

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Abstract

Effective interpersonal coordination is fundamental to robust social interaction, and the ability to anticipate a co-actor's behavior is essential for achieving this coordination. However, coordination research has focused on the behavioral synchrony that occurs between the simple periodic movements of co-actors and, thus, little is known about the anticipation that occurs during complex, everyday interaction. Research on the dynamics of coupled neurons, human motor control, electrical circuits, and laser semiconductors universally demonstrates that small temporal feedback delays are necessary for the anticipation of chaotic events. We therefore investigated whether similar feedback delays would promote anticipatory behavior during social interaction. Results revealed that co-actors were not only able to anticipate others' chaotic movements when experiencing small perceptual-motor delays, but also exhibited movement patterns of equivalent complexity. This suggests that such delays, including those within the human nervous system, may enhance, rather than hinder, the anticipatory processes that underlie successful social interaction.

Key words: anticipatory synchronization; interpersonal coordination; chaos; global coordination; complexity matching

Coordinating one's movements and actions with those of another individual is fundamental to successful social interaction. In most instances, such interaction is effortless and efficient, even when we are faced with highly variable and often unpredictable behavioral events. Key to achieving coordination and cooperation in this context is being able to predict or anticipate the behaviors and actions of other individuals. The majority of research investigating the perceptual-motor mechanisms that support behavioral anticipation has been based on hypotheses about neural simulation processes (Blakemore & Decety, 2001), feed-forward internal models and motor programs (Noy, Dekel, & Alon, 2011), or shared intentional and representational states (Sebanz, Bekkering, & Knoblich, 2006). These and similar constructs have been formulated to account for how the human nervous system compensates for the temporal delays that inherently occur between the production of a movement and the perception of its outcome (i.e., feedback). The traditional assumption is that perceptual-motor feedback delays present a problem for coordinating behavior because in linear systems theory feedback delays amplify errors and lead to instability (Stepp & Turvey, 2010).

In contrast to the idea that feedback delays promote instability, recent work examining the dynamics of laser semiconductors (e.g., Sivaprakasam et al., 2001), coupled neurons (Toral et al., 2003), and electrical circuits (Voss, 2002), as well as work on human motor control (Stepp, 2009), has found evidence that small temporal feedback delays actually enhance the ability for a system to synchronize with unpredictable, chaotic events. This counterintuitive phenomenon, referred to as *self-organized anticipation* or *anticipatory synchronization*, has been found to emerge when a "slave" system (i.e., electronic circuit or motor process) is unidirectionally coupled to a chaotically behaving "master" system (i.e., a second electronic circuit or a continuously moving environmental stimulus). As the slave system begins to synchronize with the chaotic behavior of the master system, small temporal delays are introduced into the feedback loop between the slave's behavior and the resulting outcomes of that behavior. Surprisingly, following the introduction of these delays, the actions of the slave system begin to anticipate the ongoing behavior exhibited by the chaotic master system. In other words, a small temporal feedback delay in these systems appears to support, rather than hinder, anticipatory behavior by prospectively tuning the behavior of the slave system to the evolving dynamics of the master system (Stepp & Turvey, 2008).

Stepp (2010) indicates that in order for a physical system to achieve anticipatory synchronization with respect to another physical system, the potential behavior states for both systems must first be similarly constrained, and the slave system must be sensitive to these constraints. The slave system can then be understood as embodying the constraints, and consequently the inherent dynamics, of the master system. Notably, it appears that the frequency of behavior to be synchronized has an impact on the constraints of coordinating systems and subsequent success at synchrony, such that primarily reactive behavior is observed at relatively lower movement frequencies for a variety of tasks (Hayashi & Sawada, 2013). With the introduction of a feedback delay with respect to the outcomes of its own behavior, a slave system must actually perform in an anticipatory manner in order to synchronize with the master system. The ability of the slave system to successfully anticipate the chaotic behavior of a master system in this context can thus be understood as a function of the embodiment of the master system dynamics, along with the need to act ahead of the master system in order to maintain synchrony while experiencing a delay.

Given that anticipating others' behavior is conducive to effective social interaction, but often challenging when such behaviors are seemingly unpredictable, a provocative hypothesis is that small feedback delays might also promote the ability of individuals to anticipate the chaotic movements of other people. The current study was designed to determine whether anticipatory self-organization would occur when two individuals interacted to perform a joint motor coordination task. More specifically, we examined whether the introduction of small perceptual-motor feedback delays enabled a naïve coordinator to anticipate the chaotic movements of another actor. Of particular interest were the local, short-term lead/lag patterns of coordination that occurred between the two actors, and whether the presence of small feedback delays would result in one actor anticipating (i.e., leading) the highly variable and chaotic movements of the other. We were also interested in characterizing the long-term structure of the actors' movement dynamics, as recent research has found evidence that individuals can embody the global structure and behavioral complexity of those with whom they interact (e.g., Coey, Washburn, & Richardson, 2014; Delignières & Marmelat, 2014). Such 'global coordination' appears to be a signature of self-organized anticipation because it indicates that the behavioral dynamics of each actor are self-similar and long-range dependent (Delignières & Marmelat, 2014)—meaning that each actor will display recurrent patterns of sensorimotor variability over a broad range of time scales. This global coordination can be quantified by comparing the fractal (i.e., self-similar) structure of the behavioral variability found within each of the two actors' concurrent, coordinated behaviors to determine whether the complexity of the two behavioral sequences match (so-called *complexity matching*).

Method

Participants

Twenty-two students (11 pairs) were recruited from the University of Cincinnati to participate in the experiment. Participants ranged in age from 18 to 27 years.

Procedure and Design

Pairs of naïve participants completed a task in which one participant was assigned to the role of movement "producer" and the other participant was assigned the role of "coordinator." The producer in each pair was instructed to create continuous, aperiodic (chaotic), elliptical movement sequences[1], while the coordinator was instructed to synchronize his or her own movements with those of the producer (supplementary materials, materials and methods). For this task, the coordinator filled the role of the slave system, and for each experimental trial the coordinator experienced either no perceptual feedback delay or one of three short temporal delays (200, 400, or 600 ms) with respect to the outcome of their own movements. Participants sat back-to-back, each facing their own display monitor (50" HD Plasma TV), and were equipped with a motion sensor attached to the middle joint of the first two fingers of their right hands**.** Producer movements were displayed on both screens as a red dot (2 cm in diameter), and coordinator movements were displayed as a blue dot (2 cm in diameter). These dots appeared on the right half of the producer's screen and the left half of the coordinator's screen (the other half of the screen was covered). The display was generated by an application written using C/C++ and OpenGL. A Polhmeus Liberty magnetic tracking sensors (Polhemus LTD, Colchester, VT) were used by participants to control their visual stimulus. The OpenGL program was also used to record the movement data collected by the Polhemus motion sensors, at a sampling rate of 120 Hz.

Past investigations of anticipatory synchronization (Sivaprakasam et al., 2001; Stepp, 2009; Toral et al., 2003; Voss, 2002) have involved a unidirectional coupling between subsystems whereby the slave system gains information about the master system, but not vice versa. However, social interaction often involves a bidirectional coupling, or mutual enslavement, between actors such that both actors have information about the other's behaviors through one or more sensory modalities. In the current study, two visual coupling conditions between the producer and coordinator participants were utilized, both of which involved the mutual enslavement characteristic of most joint action tasks. That is, the producer (i.e. 'master' system), as well as the coordinator (i.e., 'slave' system) always had the opportunity to see each other's behaviors with respect to their own. This not only allowed us to test whether anticipatory synchronization can occur in a bidirectionally coupled master-slave system, but also provided an opportunity to examine how the information available to the producer (i.e., master) about a coordinator's movements might affect the producer's behaviors and, subsequently, the occurrence of anticipatory synchronization.

The first, *congruent*, visual condition was designed so that both individuals had the same information about the coordinator's behavior; the producer saw the coordinator's movements at the same perceptual delay that the coordinator experienced. In the second, *incongruent*, condition the producer always viewed the coordinator's movements in real time while the coordinator saw his or her own

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[1] During two practice trials, the producer was asked to coordinate with fully chaotic, simulated sequences based on the equation for a "chaotic spring" system. The observation of positive average largest Lyapunov exponents (LLEs) for each participant indicates that the behavioral dynamics produced were consistent with chaos.

movements with a feedback delay. This situation introduced the possibility that, should anticipatory synchronization occur, the producer would perceive the coordinator's movements as leading their own. If anticipatory synchronization was dependent on having a master system that operates independently of slave system behavior, we might expect that allowing producers to perceive that coordinator behaviors occur before their own would result in a breakdown of the coordination, or a switching of co-actor roles such the coordinator, rather than the producer, would begin to drive the patterns of social motor coordination. However, if anticipatory synchronization is to be useful in understanding complex, interpersonal coordination then it must still occur in the context of bidirectional coupling between co-actors, and necessarily when both actors are able to see the other's behavior in real time. Accordingly, the bidirectional visual coupling conditions employed in the present study provided a test of whether self-organized anticipation can be achieved between mutually enslaved subsystems, as well as whether different forms of bidirectional coupling might differentially impact resulting coordination and anticipation.

Data Analysis & Results

Cross-Correlation and Phase Lead

To determine whether anticipatory synchronization occurred between coordinators and producers, we first performed a cross-correlation analysis between the movements of the coordinator and producer. This analysis indexes the degree of synchrony between two behavioral time series across a range of possible temporal relationships (see Stepp, 2009). Of relevance for determining anticipatory synchronization is the maximum degree of synchrony that occurred (indexed by the maximum observed cross-correlation coefficient) and the corresponding time lag (or lead) at which the synchrony occurred. Although the maximum cross-correlation results revealed that the coordinators were able to coordinate their movements with those of the producers (Figure 1), when coordinators did not experience delayed feedback about their own movements no anticipation (as measured by the time lag/lead at which the maximum cross correlation coefficient was found) was observed (Figure 1). Consistent with the phenomenon of anticipatory synchronization, however, in the 400 ms feedback delay condition the movements of the coordinator began to lead those of the producer, indicating that the coordinator was in fact anticipating the producer's chaotic (i.e., fundamentally deterministic, yet unpredictable) movements. A smaller degree of anticipatory synchronization was also observed for the 600 ms feedback delay condition, but overall the stability of coordination at this delay was poor in comparison to the other delay conditions. Consistent with our observation of participants performing the task, it appears that the 600 ms delay simply makes the coordinator's goal of synchronizing so difficult that coordination in general is no longer well supported. Interestingly, the congruency of the visual coupling had no influence on the behavioral patterns of coordination observed for the different feedback delay conditions. Moreover, compared to what has been observed in the context of unidirectional actor-environment coupling (Stepp, 2009), the bidirectional nature of the visual coupling employed in the current study appeared to have little effect on the emergence of anticipatory synchronization. This finding is critical to the understanding of anticipatory self-organization as an interpersonal coordinative process, as many complex social behaviors inherently involve mutual enslavement and information flow between actors.

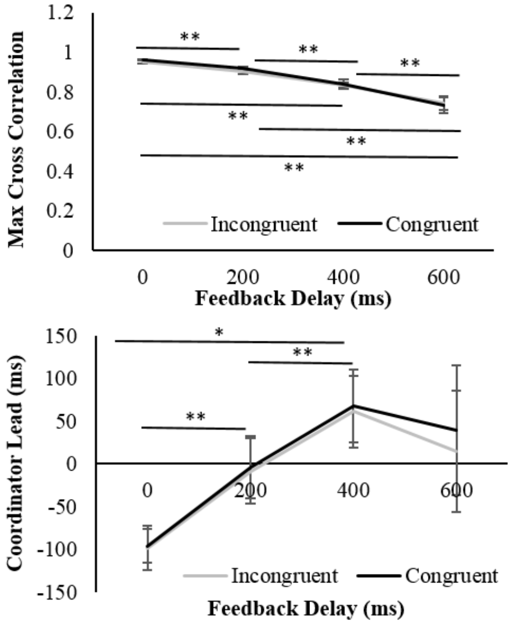

Figure 1: Cross-correlation and temporal lead. (Top) Average maximum cross-correlation between coordinator and producer movements. (Bottom) Average temporal lead between coordinator and producer movements. Line graphs in this figure are presented as means ± SEM. $**p < .005$, $*p < .05$; two-way analysis of variance (ANOVA) with Fisher's LSD post hoc comparisons.

Instantaneous Relative Phase

To confirm the cross-correlation results, an analysis of the relative phase between the movements of the coordinator and producer in each participant pair was conducted. Relative phase captures the spatial-temporal patterning of the coordination that occurs between two movement time-series (see Lopresti-Goodman et al., 2008). Of particular relevance for the current study was the distribution of relative phase angles that occurred for each feedback delay condition (i.e., how often a particular relative phase relationship was observed between the coordinator and producer over the course of a behavioral trial), with peaks in the distribution indicative of the stability of the coordination (higher peaks = higher stability) and the degree to which the coordinator led or lagged behind the movements of the producer (Figure 2).

Consistent with the results of the maximum cross-correlation analysis, the relative phase distributions indicated that the coordinator did indeed anticipate the aperiodic movements of the producer for the 400 ms feedback delay condition. Additionally, although a modest degree of anticipatory behavior was observed for the 600 ms condition, the stability of the phase relationship between the coordinator and the producer at this feedback delay was again found to be very low. More interestingly, however, the distributions of relative phase didn't just reveal anticipatory behavior on the part of the coordinator for the 200 ms condition. They also showed that for this condition, as well as for the 400 and 600 ms feedback delay conditions, coordinators both lagged and led producer movements, suggesting that the anticipatory synchronization observed was intermittent. Intermittent, or relative, coordination is a known characteristic of weakly coupled physical or biological limit-cycle oscillators (see Kelso & Ding, 1993), including visually coupled rhythmic limb movements of co-acting individuals (Schmidt & Richardson, 2008). While this has never before been demonstrated with respect to anticipatory synchronization in the context of feedback delays, evidence of similar intermittent leading and lagging behavior has previously been observed within the mutual interactions of coordinated musicians (Wing et al., 2014).

Box Counting

As mentioned above, recent research has demonstrated that the movements of interacting individuals do not only become entrained on a local or synchronous time-scale but can also become matched with respect to their long-term statistical structure and behavioral complexity (e.g., Coey et al., 2014; Delignières & Marmelat, 2014). Such global coordination or complexity matching provides further evidence of self-organized anticipation by demonstrating that the behavior of co-actors is self-similar and long-range dependent. As these characteristics are directly related to patterns of behavioral variability exhibited across several timescales, we were interested in measuring the long-term global coordination that occurred between the co-actors as a complement to our assessments of the local (short-term). To determine whether the movements of the coordinator were globally coordinated with the chaotic dynamics of the producer's movements, we assessed the spatial self-similarities between producer and coordinator movements during each trial by calculating the correlation between the fractal dimension (FD) of producer and coordinator movements in the 2-dimensional movement plane (i.e., for the 'x' and 'y' dimensions parallel to the 'x' and 'y' dimensions of the display screen). The results revealed significant evidence of complexity matching in that there was a very strong positive relationship between the FD of producer movements and the FD of the associated coordinator movements (Figure 3). This was the case irrespective of visual condition and feedback delay condition, although the relationship was weakest for the 600 ms feedback delay condition and highest for the 200 ms feedback delay condition.

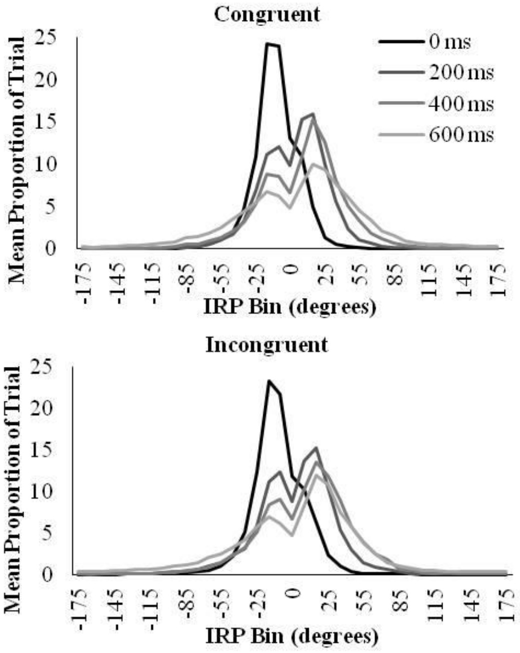

Figure 2: Distribution of instantaneous relative phase (IRP). Average values between coordinator and producer movements for the congruent visual condition (top) and incongruent visual condition (bottom) over the course of a trial, for each feedback delay condition.

There remains some debate as to whether local and global coordinative processes are mutually exclusive, or whether one or the other is more likely to occur in specific contexts (see Stephen & Dixon, 2011 for further details). To address this question for the current task, correlations between the average maximum cross-correlation and the average difference between coordinator and producer FDs were calculated for the different delay and visual coupling conditions. This analysis revealed no consistent relationship (a significant relationship between the two variables was only found at the 400 ms feedback delay in the incongruent visual coupling condition, $r(9) = -.72$, $p < .05$), indicating that the degree of complexity matching and global coordination observed within a given trial was not entirely dependent on the level of local or synchronous behavioral coordination achieved. In other words, coordinators appear to have embodied the long-term structure of the producers' chaotic movements regardless of the strength of the local coordination observed.

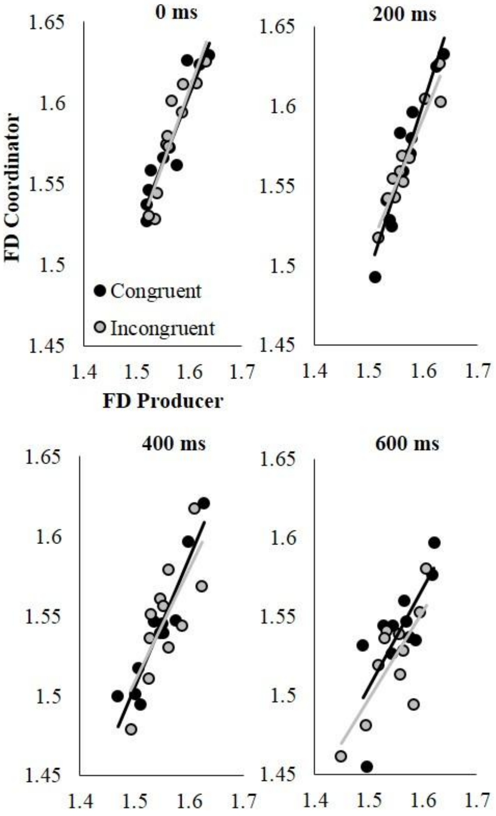

Figure 3: Complexity Matching. Scatterplots show average fractal dimensions (FD) for producer and coordinator movements, by participant pair, for each combination of visual conditions and feedback delay conditions. All Pearson correlations were significant, $p<.01$.

Discussion

The current study was designed to determine whether anticipatory synchronization of chaotic movement behaviors could occur during human social interaction. Our findings demonstrate that the short perceptual feedback delays necessary for an actor to achieve anticipatory synchronization in an intrapersonal (i.e., non-social) actor-environment context (see Stepp, 2009) also appear to be critical for anticipatory synchronization in a social coordination context. More specifically, feedback delays around 200 ms to 400 ms were observed to be most effective in facilitating anticipation, with a significant breakdown in coordination being observed for the longer delay of 600 ms. These results indicate that the very short temporal delays known to exist within the human sensorimotor system (e.g., Wallot & Van Orden, 2012) may therefore be fundamental to the production of anticipatory behavior, and ultimately serve to facilitate the production of stable coordination patterns, rather than destabilize motor performance as is often assumed.

It is important to note that the experimentally introduced delays used here are superimposed on top of the delays already inherent within the human sensorimotor system, and likely provide an exaggerated view of the naturally occurring anticipatory processes that result from existing delays. In fact, the ability of an actor to coordinate with the chaotic behaviors of their co-actor, at a very short temporal lag and in the absence of any experimentally introduced feedback delay, may itself be evidence for naturally occurring anticipatory synchronization (Stepp & Turvey, 2010). Indeed, successful anticipatory behavior does not necessarily require that an actor consistently lead a co-actor's behavior, as is indicated by the intermittency of the anticipatory synchronization observed here. Rather, the outcome may be constrained to the maintenance of a functional level of synchronization, but with increases in feedback delay (up to around 400 ms) supporting an exaggerated expression of naturally occurring behavioral anticipation.

Notably, our findings also demonstrate that anticipatory synchronization can be achieved within a system made up of two bidirectionally coupled co-actors. Even within the *incongruent* visual coupling condition, in which the producer could have noticed that coordinator movements were ahead of their own, the same anticipatory relationship between coordinator and producer movements was achieved. The current findings therefore indicate that it is not actually necessary for one to be "ahead" in order to be driving coordinated joint-action. On the contrary, it appears that functional coordination of such complex behaviors is varied, flexible, and resilient to small fluctuations in the phase relationship between movements.

The self-organized anticipation underlying such local, interpersonal coordinative behaviors also appears to have resulted in global coordination, or complexity matching between co-actors. However, while feedback delays around 200-400 ms seem to promote high levels of local behavioral anticipation, the occurrence of global coordination between actors does not appear to be influenced by the introduction of these short delays (the 600 ms delay appears to disrupt the stability of coordination at all levels examined). Previous studies have demonstrated, however, that complexity matching for one system with respect to another is dependent on pre-existing statistical self-similarity of the behavior that a coordinating system or individual is trying to match (Delignières & Marmelat, 2014). Ultimately, this allows the coordinating system to exploit the existing complexity of this ongoing behavior, in order to produce more adaptive and efficient behavior with respect to any task goal (Delignières & Marmelat, 2014). For a bidirectionally coupled system, the complexity within each component subsystem provides an opportunity for mutual adaptation and bidirectional anticipation (Delignières & Marmelat, 2014) that can lead to corresponding fluctuations in behavioral variability (e.g., changes in movement trajectory and velocity). Therefore, the chaotic behaviors produced in the current task are understood as supporting self-organization of both local and global coordinative phenomena.

Both the local anticipatory behavior and global complexity matching of interacting individuals observed here are understood to be natural consequences of the universal, lawful dynamics that shape and constrain the time-evolving structure of behavior. Although many biological and human behaviors may be chaotic (see Newell, Deutsch, & Morrison, 2000), they are still lawful and deterministic. This implies that the behavioral dynamics of all human, perceiving-acting agents are constrained by the same physical laws of energy dissipation and information flow, and that these intrinsic commonalities in behavioral order allow for the self-organized emergence of anticipatory coordination (Stepp & Turvey, 2008). The dynamics of delay-induced anticipatory synchronization might therefore provide a lawful explanation for how and why we can achieve the robust social anticipation and coordination that underlies everyday activities. Whether navigating a busy sidewalk, loading a dishwasher with a family member, or coordinating ones movements with others during team sports, such an explanation no longer requires recourse to a set of internal, 'black-box' compensatory neural simulations, representations, or feed-forward motor programs.

Acknowledgments

This research was supported by the National Institutes of Health (R01GM105045).

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