Anticipatory Synchronization in Artificial Agents

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Abstract

By integrating theories and methodologies from a diverse range of scientific disciplines (e.g., physics, neuroscience, cognitive science, psychology and robotics engineering) the present work is aimed at harnessing self-organized anticipatory synchronization in order to advance human-robotic interaction (HRI). This phenomenon is characterized by the emergence of anticipatory behavior by one system coupled to the chaotic behavior of another, following the introduction of short self-referential delays in the coordinating system. The current set of studies involved the creation of an artificial agent based on a time-delayed, low-dimensional dynamical model capable of behaving prospectively during an interaction with a human actor performing complex, unpredictable behaviors. By achieving characteristics similar to those observed during natural human interaction and coordination, the time-delayed modeling approached advocated here provides the potential for considerable future advancements in HRI.

Key words: human-robotic interaction; artificial agents; dynamical modeling; virtual reality; anticipatory synchronization; interpersonal coordination; chaos

Rapid advances in cyber-technologies and robotics present increasing opportunities for the implementation of interactive, artificial agents within contexts of human behavior. This includes, but is not limited to, assistance during the performance of everyday tasks and the development of new skills. Work has already been done, for example, on the development of virtual agents able to assist elderly individuals with the organization of their daily activities (Yaghoubzadeh et al., 2013), and to create a robot whose structured interaction may help to improve interpersonal coordination in children with autism spectrum disorders (Palatinus, 2014). However, Lorenz and Hirche (2014) have recently drawn attention to the fact that engineers working to design virtual and robotic agents do not always prioritize those aspects which will allow for smooth, effortless human interaction, while psychologists studying interpersonal or joint-action do not always take into account technical realizability in describing what they see as the fundamental elements of successful multi-agent coordination.

One potential solution to this issue is to identify and model the behavioral dynamics (Warren, 2006) of natural human-human interaction using low-dimensional differential equations that can be easily implemented within interactive robotic or machine systems. Recent work by Dumas et al. (2014) and Zhai et al. (2014) has already provided support for the idea that relatively simple self-sustaining, nonlinear dynamical systems can be used to construct virtual interaction partners capable of successful, flexible coordination with human actors. Both groups of researchers used long-standing oscillator models of biological coordination to develop virtual agent systems capable of synchronizing with a selection of behaviors exhibited by a human actor. For instance, Dumas et al. (2014) have developed variations of their Human Dynamic Clamp (HDC) system that can coordinate with continuous and discrete finger movements of a human actor. Zhai et al. (2014) have designed a similarly adaptive virtual agent that is capable of coordinating with an individual during a continuous, one-dimensional movement-mirroring task.

The development of these dynamical, artificial agents has primarily focused on their ability to exhibit coordination with periodic behaviors, or synchronize with fluctuating movement speeds using a velocity estimation algorithm. However, one only has to consider a pedestrian navigating a busy city sidewalk to be reminded that people are often capable of prospectively coordinating their behavior with highly variable, seemingly unforeseeable events in an effortless manner. Recent research in human motor control and joint-action has demonstrated that small perceptual-motor feedback delays, such as those known to exist within the human nervous system, may actually facilitate the ability to achieve anticipation of such continuous chaotic events (Stepp, 2009; Washburn et al., 2015). This phenomenon, referred to as *strong anticipation* or *self-organized anticipatory synchronization*, has been found to emerge when a unidirectional coupling exists between a "slave" system and a chaotically behaving "master" system (e.g., Masoller, 2001; Stepp & Turvey, 2015; Voss, 2000). Surprisingly, as the slave system begins to synchronize with the chaotic behavior of the master system, the introduction of small temporal feedback delays results in the slave system anticipating the ongoing behavior exhibited by the chaotic master system.

Of particular significance here, is that the dynamics of chaotic anticipation during interpersonal coordination can be captured using a low-dimensional dynamical model and can be easily implemented in artificial agents. Such models of self-organized anticipatory synchronization could therefore provide an opportunity for significant advancement in HCI and HRI through the development of artificial systems capable of anticipating chaotic human behavior during real-time interaction. In the current study, two experiments were conducted to examine whether a virtual, artificial agent, whose arm movements were controlled by a time-delayed dynamical model, could not only coordinate with the chaotic movements of human actors in real time, but could do so in a self-organized anticipatory manner akin to human-human perceptual-motor coordination.

Method

Participants

Twelve students were recruited from the University of Cincinnati to take part in Experiment 1 along with four individuals from the greater Cincinnati area, for a total of 16 participants. Participants ranged in age from 19 to 31 years.

Seventeen University of Cincinnati undergraduate students participated in Experiment 2 (eight in the 1.5 coupling strength condition and nine in the 2.0 coupling strength condition). Participants ranged in age from 18 to 31 years.

Procedure and Design

A virtual reality (VR) interface was employed in both experiments as it afforded the opportunity to examine the phenomenon of human-human and human-machine anticipatory synchronization within a realistic, yet highly controllable setting. A seated participant interacted with a simple virtual environment created using Unity 3D and viewed via a head-mounted Oculus Rift. Within the virtual environment participants saw a robot avatar sitting directly in front of them, and an additional avatar arm that moved along with their own right arm movements. The movements of this virtual participant arm were generated through the inverse kinematics function available within Unity 3D by coupling the pointer finger of the virtual arm to the real time position of a wired motion sensor attached to the first two fingers of a participant's right hand. A Polhemus Liberty electro-magnetic motion capture system (~0.1 mm accuracy) (Polhemus Liberty, Polhemus Corporation, Colchester, VT) was used to record and track participants' movements at 120 Hz. The horizontal and vertical coordinates of participant movement were also recorded from the magnetic tracking system at a sampling rate of 75 Hz for later analysis. The receiver for this system was positioned approximately 10 cm in front of the fingers of a participant's right arm outstretched directly in front of their body.

Experiment 1: Human (slave) – Avatar (master) Experiment 1 was designed to establish the coordinative dynamics exhibited by human actors coordinating with an artificial agent via a novel VR setup. That is, we examined whether small perceptual-motor feedback delays could enhance a human actor's ability to anticipate the chaotic movements of the artificial agent system. Experiment 1 was also conducted to assess the degree to which bidirectional coupling (from master to slave) might influence the emergence of anticipatory synchronization. At the beginning of each experimental trial, the robot avatar began to move its left arm with the index finger pointed in a continuous trajectory. The participants' task was to synchronize their own arm movements with those of the moving stimulus (in this case the robot avatar's arm). The movements of the robot avatar (master system) were defined online by means of a chaotic spring system,

$$\dot{x}_1 = x_2 + C(p_1 - x_1)$$

$$\dot{x}_2 = -(\omega\pi\left(\frac{x_3}{\alpha} + \beta\right))^2 x_1 + C(p_2 - x_2)$$

$$\dot{x}_3 = -x_4 - x_5$$

$$\dot{x}_4 = x_3 + \alpha x_4$$

$$\dot{x}_5 = b + x_5(x_3 - c)$$

with the $x_{3,}x_4$ and x_5 dimensions defining a standard Rössler attractor (Stepp, 2009). This attractor generates the chaotic dynamics used to define position of the 'x' and 'y' dimensions for a simple harmonic oscillator specified in x_1 and x_2. The resulting system maintains an elliptical trajectory over time while exhibiting chaotic fluctuations in amplitude and frequency. Nine sets of system parameters a, b, c, α, β, ω and initial conditions x_1, x_2, x_3, x_4, and x_5 were selected for use based on support of the evolution of bounded chaotic behavior.

Generating this behavior online allowed us to introduce a coupling term, C, between the virtual robot avatar and the behavior of the human participant. This system included an influence of the 'x' coordinates of a participant's arm movements, p_1, on the ‘x’ coordinates of robot avatar arm movements, x_1, as well as a symmetrical influence of the ‘y’ coordinates of participant arm movements, p_2, on the ‘y’ coordinates of the robot avatar arm movements, x_2. The weight of avatar-participant coupling was manipulated to allow for more or less influence of the movement of the participant on that of the robot avatar, resulting in three total coupling strength conditions (0, .025, and .05). Feedback delays of 26.67[1], 200, and 400 ms were introduced between the participant’s movements and the movement of their virtual arm. The average movement frequency exhibited by the robot avatar for a given trial in this study was between .23 and .30 Hz[2]. Trials lasted 60 s. The first 10 s and last 5 s of each time series were discarded to remove transients.

Experiment 2: Human (master) – Avatar (slave) Experiment 2 examined whether an artificial agent, as a slave system, could anticipate the chaotic movements of a human master system. Participants were initially asked to complete two training trials in which they were to synchronize with robot avatar movement defined by fully chaotic, 2-D movement sequences generated ahead of time (i.e., there was no influence of participant movements on robot avatar master system behavior). The same two chaotic robot avatar movement sequences[3] were provided to all individuals. During these trials participants saw their own virtual arm within the environment at the minimum delay possible (i.e., 26.67 ms). Each sequence lasted 100 s. For the remainder of the experiment participants were asked to continue making the same kinds of movements they had been making during the training period: “generally circular and always in the same direction, but somewhat unpredictable in terms of the speed and size of movements”. They were also informed that they would be switching roles with the robot avatar, so that they were now the leader and the avatar would be coordinating with their movements. For these test trials the system of equations specifying the baseline slave behavior of the robot avatar consisted of a harmonic spring oscillator[4]

$$\dot{x}_1 = x_3 + C(m_1 - x_{1d})$$

$$\dot{x}_2 = x_4 + C(m_2 - x_{2d})$$

$$\dot{x}_3 = -\omega x_1$$

$$\dot{x}_4 = -\omega x_2$$

As in the harmonic spring system used in the previous experiment, this system includes a coupling term, C, here to modulate the strength of coupling between the robot avatar and the ‘x’, m_1, and ‘y’, m_2, dimensions of a 2-D master system (i.e., human participant) behavior. This method of *delay-coupling* results in a function that incorporates the ‘x’ and ‘y’ dimensions of its’ past behavior, x_{1d} and x_{2d}, into the terms that reference the velocity of movement in each of the ‘x’ and ‘y’ dimensions, x_3 and x_4, effectively constituting a feedback delay within the system (see Stepp & Turvey, 2015; Voss, 2000). Here the past behavior being referenced, x_d, is always that which occurred at a constant, set length of time, τ, prior to the current time point, t,

$$x_d = x(t - \tau)$$

The remaining terms in the system of equations responsible for robot avatar movement include the variable specifying spring stiffness, ω, through interaction with the ‘x’ and ‘y’ position variables, x_1 and x_2. Two different values for the slave-master coupling term, C, were introduced within this system (1.5 and 2), and were treated as a between subjects variable such that participants either interacted with the avatar system coupled to them with the lower or higher strength. Five different delay latencies were also introduced within the robot avatar system as τ (26.67, 106.64, 199.95, 306.59, and 399.90 ms). These coupling strengths and delay latencies were chosen based on preliminary simulations using a chaotic spring master system and the current harmonic spring oscillator slave system. Each delay latency was instituted once per participant, with the order of presentation randomized over the five test trials experienced by each participant. Each trial lasted a total of 60 s. As in Experiment 1, the first 10 s and last 5 s of each time series were discarded for analysis.

Data Analysis & Results

Largest Lyapunov Exponent

Calculation of the largest Lyapunov exponent (LLE) provided an initial measure of the chaotic dynamics within master system movement time series (see Washburn et al., 2015 for details). Average LLE values of robot avatar movement sequences from Experiment 1 were all positive (M = 0.024, SD = 0.008), indicating that the robot avatar exhibited consistent chaotic movement dynamics even when it was coupled to the coordinating behavior of the human participant. LLE values associated with human participant

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[1] Motion tracking (~5.32 ms) and data transfer (~5 to 8 ms) time, plus screen refresh rate (~13.33 ms) resulted in a minimal delay between a participant’s movement and rendering of 26.67 ms.

[2] Individuals creating similar chaotic movement sequences produced behavior with the average frequency for a given trial between .14 and .57 Hz, and an overall average frequency of .32 Hz (Washburn et al., 2015).

[3] Washburn et al. (2015) used these sequences to train individuals to act as master systems during interpersonal anticipatory synchronization and demonstrated that the training consistently led to individuals producing chaotic movement behavior.

[4] Harmonic spring systems are flexible with relatively few intrinsic dynamics. For slave systems with inherently chaotic dynamics it will be harder to evaluate whether anticipatory behavior of another chaotic system is primarily a product of coordination.

behavior in Experiment 2 were also positive for all combinations of feedback delay latency and slave-master coupling conditions except one (feedback delay: 26.67 ms, avatar-actor coupling: 2.0) (overall M = 0.034, SD = 0.046), indicating that the participants produced reasonably consistent chaotic movement dynamics when acting as the master system.

Cross-Correlation and Phase Lead

To evaluate whether anticipatory synchronization occurred between the slave and master systems in Experiments 1 and 2, we first performed a cross-correlation analysis. This analysis indexes the degree of synchrony between two behavioral time series across a range of possible temporal relationships (Stepp, 2009). Of relevance for identifying 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.

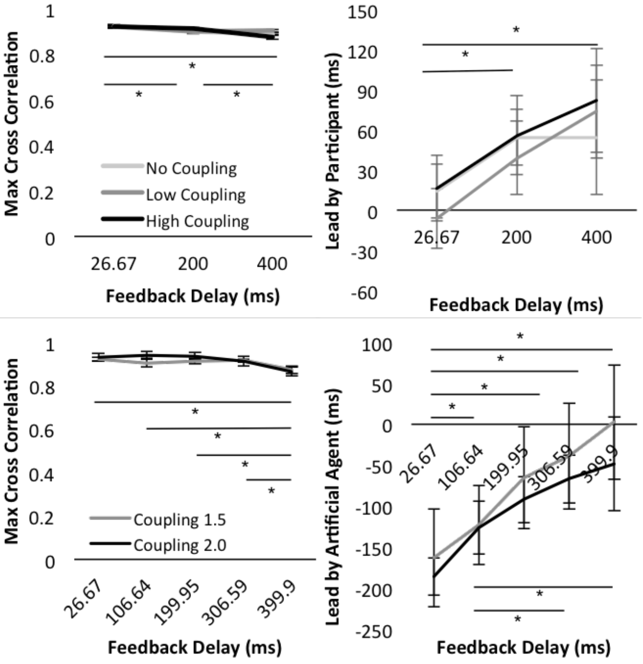

Figure 1: Average maximum cross-correlation (left) and temporal lead/lag (right) between artificial agent and human participant movements for Exp. 1 (top) and 2 (bottom). Line graphs in this figure are presented as means ± SEM. **p*< .05; two-way analysis of variance (ANOVA), using Bonferroni post hoc comparisons.

The results of this analysis for Experiment 1 were very similar to those found in previous studies of human anticipatory synchronization (Stepp, 2009; Washburn et al., 2015). Namely, that although overall coordination decreased slightly with increases in perceptual-motor feedback delay, anticipatory synchronization was observed for delays between 200-400 ms (Fig. 1, top). Interestingly, no significant differences in anticipation were observed for the different coupling strengths employed. This is also consistent with existing studies in agent-environment and interpersonal human coordination, indicating that the VR paradigm employed here is suitable for the continued investigation of human anticipatory synchronization during uni-directional and bi-directional slave-to-master coupling situations.

In Exp. 2, maximum cross-correlation analysis also revealed a decrease in coordination with increases in time-delay, here implemented within the artificial agent slave system (Fig. 1, bottom left). More importantly, increases in time-delay were associated with a progressive decrease in lag latency between the artificial agent and human participant, with the artificial agent achieving temporal synchrony with the human participant for the 399.90 ms delay latency (Fig. 1, bottom right).

Instantaneous Relative Phase

To gain further information about the anticipatory coordination that occurred between the human and artificial agent, an analysis of the relative phase between the movements of the slave and master systems in each experiment was conducted. Relative phase captures the spatial-temporal patterning of the coordination that occurs between two movement time-series. 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 slave system led or lagged behind the movements of the master system (Schmidt & O'Brien, 1997).

IRP distributions for participant with respect to avatar movements in Experiment 1 consistently indicated the occurrence of intermittent leading and lagging behavior, with more frequent leading than lagging in all combinations of coupling strength and feedback delay conditions (see Fig. 2). This kind of intermittent, or relative, coordination is consistent with the coordinative dynamics exhibited during interpersonal anticipatory synchronization (Washburn et al., 2015), and characterizes weakly coupled physical or biological limit-cycle oscillators (see Kelso & Ding, 1993), including visually coupled rhythmic limb movements of co-acting individuals (Schmidt & O'Brien, 1997). These distributions look similar across conditions with some decreased stability apparent in the 400 ms delay condition, especially when there was no coupling from robot avatar to participant. There also seemed to be less relative difference in the frequency of leading to lagging in both of the bi-directional coupling conditions as compared to the no coupling condition at the 26.67 ms feedback delay. There were very few differences in these distributions between the low and high coupling strengths conditions examined.

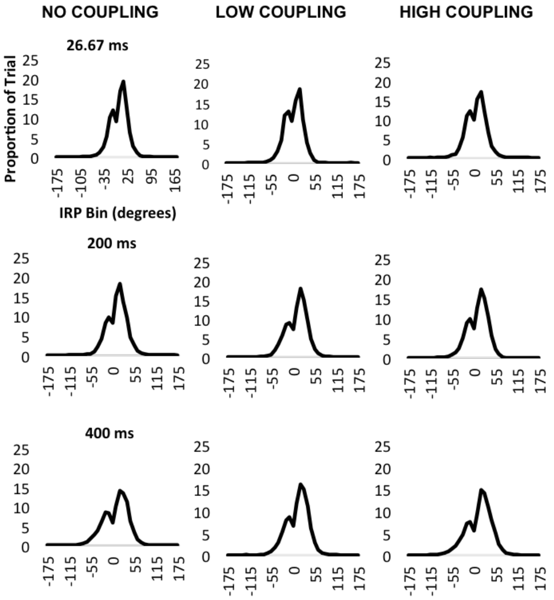

Figure 2: Distribution of average instantaneous relative phase (IRP) values between artificial agent and human actor as a function of the coupling strengths and delay conditions examined in Experiment 1.

Consistent with the maximum cross-correlation results above, when the artificial agent slave system was coupled to the live human actor master system in Experiment 2, most combinations of feedback delays and coupling strengths were associated with the artificial agent lagging behind the human actor (see Fig. 3). There was in fact relatively more anticipation than lagging at the longest feedback delay in Experiment 2 (i.e., 399.90 ms), but the overall stability the phase relationships at this delay was reduced in comparison to the shorter delays. It is important to keep in mind that both the IRP frequency distributions and the maximum cross-correlation analysis represent average phase and temporal relationships between the artificial agent and the master system to which it is coupled. Furthermore, a participant-wise examination revealed that the artificial agent achieved anticipation for three of the eight participants in the 1.5 coupling strength condition, and five of the nine participants in the 2.0 coupling strength condition. This provides strong support for the idea that the kind of artificial agent developed and tested here can produce adaptive, prospectively coordinated behavior during ongoing, bi-directionally coupled interaction with a human actor.

Discussion

The current project extends a rapidly emerging line of work investigating the process of coordination and self-organized anticipatory synchronization during human-human and human-machine interaction. The findings of Experiment 1, demonstrated that anticipation similar to that observed during interpersonal interaction is also exhibited by human actors with respect to a chaotically behaving virtual co-actor. Experiment 2 used the same novel VR paradigm to evaluate the anticipatory abilities of time-delayed artificial agent during interaction with a human co-actor. The movements of this artificial agent were defined by a low dimensional, harmonic oscillator system, coupled to the real-time behavior of the human co-actor. The results of this experiment revealed that the addition of feedback delays reduced the degree to which the avatar lagged behind the human actor.

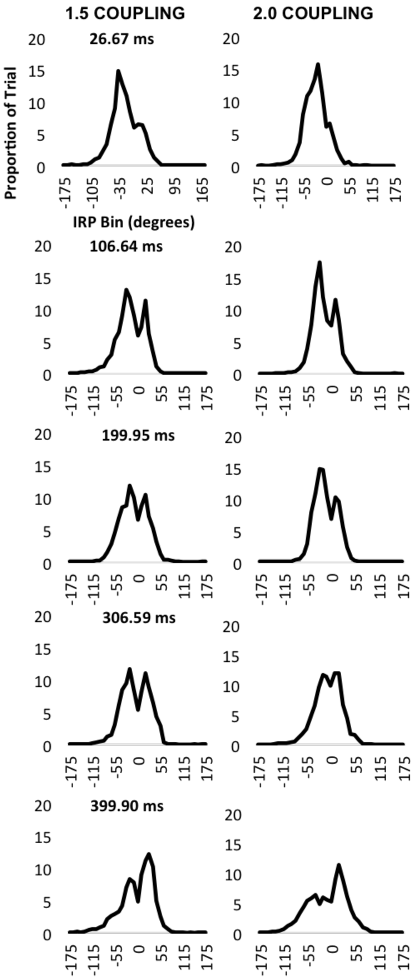

Figure 3: Distribution of average instantaneous relative phase (IRP) values between human participant and robot avatar for coupling strengths of 1.5 (left) and 2.0 (right) and in each feedback delay condition examined in Experiment 2.

It is important to appreciate that while the addition of feedback delays in the artificial agent only, on average, reduced the lag between artificial agent and the human co-actor, this should not be taken to indicate that the current agent is ill-suited to achieving self-organized anticipatory synchronization during human-machine interaction. The fact that human actors are intentional agents means they likely exhibited some adaptation to the artificial agent during interaction even though they were instructed to focus on producing their own movements and simply allow the avatar to follow them. This could account for the finding that the artificial agent only consistently achieved more anticipation than lagging of the human co-actor in the context of the longest time-delay. Furthermore, the patterns of intermittent anticipatory coordination observed in Experiment 2 were still quite similar to those seen in instances of interpersonal anticipatory synchronization, suggesting that small feedback delays in artificial agents induce a coordinative dynamic analogous to natural to human-human interaction.

Indeed, overall the current findings present a potentially transformative advance in the development of artificial agents and HRI. An agent defined by a low-dimensional dynamical model was able to display adaptive, anticipatory coordination during real time interaction with a human actor performing complex, seemingly unpredictable movements. The coordinative patterns exhibited by this agent were analogous to those observed during the occurrence of visual-motor agent-environment and interpersonal anticipatory synchronization in humans. This supports the idea that the dynamical models employed in the current research capture universal properties intrinsic to many physical systems, including complex biological behaviors like the human neural and movement processes that exhibit the kind of unpredictable determinism characteristic of chaos (e.g., Mitra et al., 1997). In displaying behavior that is qualitatively similar to human individuals the artificial agent developed here is likely capable of not only participating in the kind of interpersonal coordination known to support the successful completion of many everyday human tasks, but also engendering some of the associated increases interpersonal rapport and the facilitation of social awareness found following behavioral coordination between individuals (e.g., Miles et al., 2011). The current outcomes therefore suggest that engaging in coordinated interaction with such agents in the process of some higher order task goal will not only allow for more successful and efficient interactions during a wide variety of tasks, but may also result in the kinds of positive social outcomes associated with naturally occurring human interaction.

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