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Abstract

Complexity matching—converging temporal correlations measured by correlating the slopes of power spectra—is a new measure of coordination based on information exchange between complex networks. To date, studies have focused on the dyadic case, but complexity matching may generalize to interacting complex networks in the left and right hemispheres of a single brain. We examined complexity matching in a perceptual-motor task between individuals and dyads. Participants alternated hitting targets in a Fitts-like task with the left and right hands of one individual, or analogously between two people. Response coupling was manipulated by making targets drift randomly (decoupled) or contingently (coupled). Results showed long-range correlations in time series of inter-response intervals exhibited complexity matching for both individuals and dyads, but only when responses were coupled via contingent drift. We conclude that complexity matching observed between individuals can similarly occur within one individual, suggesting a general principle of interaction at work.

Keywords: complex systems; complexity matching; joint action; interpersonal dynamics; coordination

Introduction

From simple physical collaborations like moving furniture, to complex collaborations in sports and multi-player video games, people coordinate to accomplish shared goals. Analogous coordination also occurs within individuals, as in the bimanual coordination necessary for one person to juggle multiple balls in the air. Similarity in coordination within and across individuals is demonstrated by comparing one person juggling with two people juggling back and forth together. The goal is the same in both cases, and the hand-eye coordination necessary to juggle is similar for one or two people. Prior studies have shown that both dyadic and bimanual coordination are similarly governed by principles of coupled oscillator dynamics (Haken, Kelso, & Bunz, 1985). Another principle of coordination studies in recent years is *complexity matching*, which is based on a theory of information exchange between complex networks (Abney, Paxton, Dale, & Kello, 2014; Marmelat & Delignières, 2012; West, Geneston, & Grigolini, 2008). Complexity matching is measured as convergence in the temporal correlations produced by two given systems, where convergence is typically measured as a correlation in the estimated exponents of their respective spectra or detrended fluctuation functions. To date, studies have focused on the dyadic case, but the theory may generalize to interacting complex networks in the brain of one person. In the present study, we examined how the left and right hands coordinate to accomplish a collaborative perceptual-motor task when the hands are controlled by one individual (bimanual), versus two separate individuals (dyadic). Our aim is to test whether complexity matching generalizes across individual and dyadic coordination tasks, and whether it is similarly affected by manipulations of response coupling between the left and right hands.

Perceptual-motor coordination has been studied in terms of timing and movement accuracy (Rosenbaum, Dawson, & Challis, 2006), phase relations among oscillatory movements (Coey, Varlet, Schmidt, & Richardson, 2011), and correlations in movement dynamics (Marmelat & Delignières, 2012; Schmidt, Morr, Fitzpatrick, & Richardson, 2012; Stephen, Stepp, Dixon, & Turvey, 2008). Typically, coordination is measured in terms of a phase relation like synchronization or syncopation, but more recently complexity matching has been introduced as an alternate measure of coordination (Marmelat & Delignières, 2012; Abney, Paxton, Dale, & Kello, 2014). Marmelat and Delignières (2012) were the first to investigate the relationship between coupling strength and complexity matching. Participants worked in groups of two to swing separate pendulums back and forth using either their left or right hand. Participants first practiced the task alone using only one hand, oscillating the pendulum at their own preferred speed for approximately five minutes. Afterwards, both participants began a series of three trials in which they swung the pendulums in synchronous in-phase movements. The authors manipulated the available amount of perceivable information about the other partner. In a weak-coupling condition, only peripheral visual information was provided about the partners' swinging movements. The intermediate-coupling condition provided visual and auditory information, and the strong-coupling condition provided visual, auditory, and haptic information. Haptic information was available by instructing participants to cross their free arms together.

Results indicated that there was significantly less complexity matching in the weak-coupling condition compared with the intermediate and strong coupling conditions (there was no reliable difference between these latter two conditions). These findings suggest that when people have predictable information about each other's movements, they are better able to coordinate together.

The study by Marmelat and Delignières (2012) shows how the degree of coupling between individuals can be quantified in terms of complexity matching. However, coordinated interactions were not *necessary* to complete the tasks. The coordination observed was spontaneous and emerged implicitly as a result of perceptual-motor coupling. The actions of each individual in a given dyad were only indirectly influenced by the other, e.g. through peripheral vision (Amazeen, DaSilva, & Amazeen, 2008; Mechsner, Kerzel, Knoblich, & Prinz, 2001).

Other studies of perceptual-motor coordination have used tasks that require explicit interaction between multiple individual's actions in order to perform a collaborative task (Jordan, Schloesser, Bai, & Abney, 2017; van der Wel, Knoblich, & Sebanz, 2011). For example, Jordan and colleagues (2017) experimented with a collaborative task that necessarily required dyads to coordinate their left and right hands in order to complete the task. Dyads could neither see nor hear the other person they were working with, and the dyad condition was compared with an individual condition in which one person performed the same task with their left and right hands.

The task was to keep a drifting dot inside of a narrow rectangular box positioned in the center of the computer screen using two keys. Individuals were in control of both response keys, while each dyad participant was only in control of one of the response keys. Based on which key was being presses, the dot would move around the screen at a constant velocity. For both conditions, responses between the left and right hands were necessary for controlling the dot. If only one key was presses and held down, the dot would quickly reach the border of the screen and stop. Therefore, coordination between both hands was necessary for completing the task.

Jordan et al. (2017) found that individual performance was higher than the dyad by virtue of being better able to time and extend individual key presses, allowing for smooth movement across the screen. Precise timing of key presses was unavailable to dyads because they could not see or hear each other. Dyads adapted by pressing their keys quickly, at similar frequencies, so they could coordinate by adjusting the phase relation of their two series of key-presses. Previous research has suggested that visual information alone is not sufficient for dyads to adopt more efficient performance strategies (Knoblich & Jordan, 2003). The dyad strategy was less precise than the individual strategy, but it utilized available degrees of freedom to make coordination possible given limits on information exchanged between partners.

In the present study, we designed an experiment to test long-range correlations and complexity matching in a task where cooperative interactions were necessary for completing the task. We investigated whether complexity matching depends on coupling strength in a bimanual Fitts-like task in which performance was measured in terms of the time to complete the task (which takes movement speed and errors into account). We manipulated coupling between hands in two ways. One way was by instructing participants to perform the task as either individuals or dyads. Importantly, in both conditions, participants had to coordinate the timing of their left-hand and right-hand responses—the hands could not respond independent of one another, unlike the prior studies of implicit coordination. Second, we manipulated *response coupling* by drifting targets either at random or based on participant aiming errors (see below).

We designed our bimanual aiming task to address two main research questions. First, does the theory of complexity matching generalize across dyadic and individual (bimanual) perceptual-motor coordination? Second, does response coupling have the same effect on complexity matching in both dyadic and individual coordination? Prior research suggests that complexity matching should hold in all conditions because they all require coordination in the timing of left-hand and right-hand responses. We predicted greater complexity matching when there were more channels for coupling the two hands—the hand coupled via one nervous system for individuals, and via target dependencies in the response coupling condition for dyads.

Method

Sixty-six participants participated from UC Merced for course credit. Each participant signed a consent form explaining that participation is voluntary and they could end the experiment at any time. Of the 66 participants (50 female) who volunteered for this experiment, 47 females and all 16 males were right handed, based on which hand they use for writing.

Apparatus

Participants sat roughly 30 cm (11.81 in) in front of a 22-inch Planar PCT2235 touch screen monitor at approximately a 65° angle. The height of each chair relative to the table was set to a comfortable level for each participant. Two of these monitors were used, linked between two isolated lab rooms across from each other. Both rooms were 7 feet by 9 feet in size. The touch response coordinates were collected from both monitors by the same computer that ran the program used in this experiment. The program was written in Python using the Pygame module.

Procedure

The experiment began with verbal instructions about the overall nature of the task, which was to reach out and touch red circle targets as they appeared on the touch screen monitor, one at a time, as quickly as possible. Errors were also discouraged in that they delayed responding because participants had to re-touch the screen to hit the target and continue to the next target. Each red target was 2.3 cm (0.9 in) in diameter, and only one target appeared on the touch screen at a time (see Figure 1). The targets appeared in a repeated order. The first target started in the top left quadrant, the next appeared in the top right quadrant, then lower left quadrant, and finally the lower right quadrant. This cycle repeated 300 times in each block.

An auditory tone 200 ms in duration followed each response to indicate the response time. The pitch of the tone linearly related to the response time within a bounded range. The lower bound was 250Hz at 1750 ms or longer, and the upper bound was 2000Hz at 0 ms. The tone indicated performance to participants, with higher pitch meaning faster performance, and lower pitch meaning slower performance.

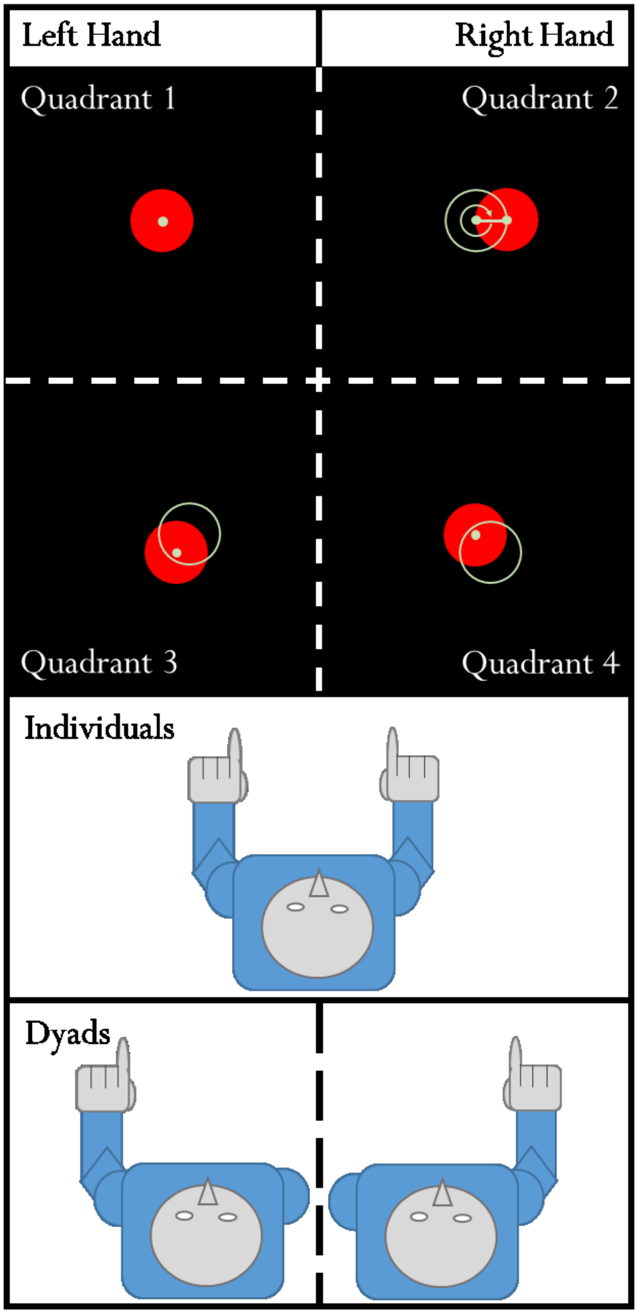

Figure 1. (Top) Depicts the four initial response locations during the individual and dyadic conditions. The white dashed lines were not visible on the screen in the experiment. Approximately to scale. (Bottom) Depicts the responses during the individual and dyadic condition. Responses in all four quadrants was required for both group types.

The left hand responded to targets in the left two quadrants, and the right hand responded to targets in the right two quadrants (see Figure 1). Participants in the individual condition used their left and right hands to respond to all targets, whereas participants in the dyadic condition responded to only half the targets. One dyad participant was chosen at random to respond to left sided targets with their left hand and the other responded to right sided targets with their right hand (see Figure 1).

All participants saw all the targets in all four quadrants, and could see the other participant's touch responses as brief gray concentric rings centered on the response location. Thus, the task stimuli and responses were the same for individual and dyadic conditions, the only difference being whether participants responded to half or all the targets.

Each experimental block of 1200 targets was preceded by 40 practice targets. Each individual participant and each dyad completed one random drift block and one dependent drift block. The order of blocks was counterbalanced across participants. Within each block, the target was repositioned within each quadrant from one response to the next, using two different algorithms. In the random drift condition, the position of each next target was determined by generating a randomly chosen new center position within the area of the previous target. This new center was translated to the next quadrant to position the next target. A new center was randomly chosen the same way after each response to create a random drift of target locations over the course of the block. In the dependent drift condition, the new center of each target was determined by the previous response location within the previous target. Therefore, dependent drift was determined by variability generated by the participants instead of a random number generator.

In both conditions, the distance of each target repositioning was no more than the target radius. In the random drift condition, if a newly generated position fell outside the boundaries of the quadrant, the target was repositioned in the opposite direction by the same distance. This boundary check kept the entire target circle in view on the touchscreen. In the dependent drift condition, newly generated positions that fell outside the boundaries were not applied—each vertical and horizontal boundary in the dependent condition kept at least half the target circle in view. The possibility of targets drifting off the screen encouraged participants to avoid the boundaries, given that they had control over the drift in the dependent drift condition.

Data collection/processing

Responses both inside and outside the targets were recorded with respect to response time and the XY response location within each quadrant. The primary dependent variable of interest is the time between consecutive target touches, i.e. the inter-response-interval (IRI). The IRI represents performance given the goal of completing each block as quickly as possible. IRIs that were above or below 2.5 standard deviations were replaced with the mean IRI for the corresponding block. The 1200 responses in each block were divided in half to identify the responses produced by the left and right hands. The last 512 responses of each hand were retained and analyzed. Figure 2 shows example IRI time series for the left and right hands from each of the four different conditions.

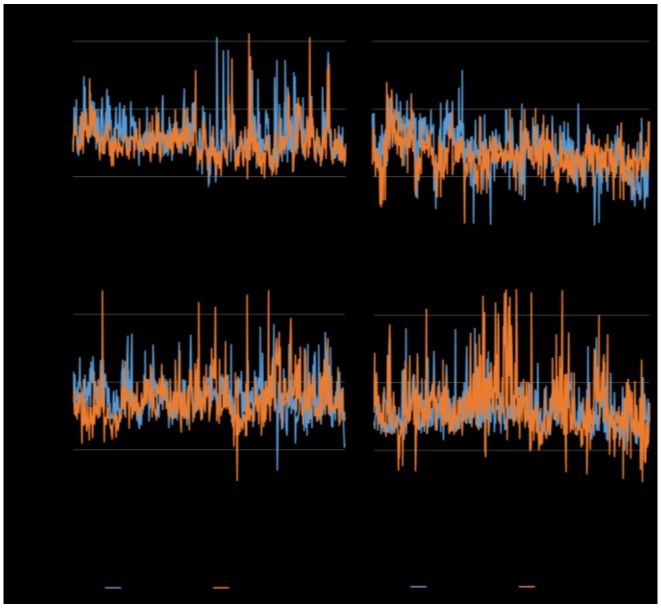

Figure 2. An example time-series for the individual random (top left), individual dependent (top right), dyadic random (bottom left), and dyadic dependent (bottom right) conditions.

Results

Total Time

We first analyzed overall performance for each condition in terms of the total amount of time it took to complete each block. A two-way analysis of variance was conducted with Group Type as a between-subjects factor (individual versus dyad), Movement Type as a within-subjects factor (random versus dependent drift), and individual or dyad as a random factor. The results indicated a significant main effect of Group Type, $F(1, 42) = 11.93$, $p = .001$, a main effect of Movement Type, $F(1, 42) = 48.08$, $p < .001$, and a significant interaction, $F(1, 42) = 5.92$, $p = .019$ (see Figure 3). Individuals were faster than dyads, the coupling of dependent drift supported faster responses compared with random drift, and individuals were better able to take advantage of dependent drift compared with dyads.

Error Rates

The same two-way ANOVA was conducted on the mean number of errors in each condition. There was only a significant main effect of Group Type, $F(1, 42) = 21.48$, $p < .001$, showing that individuals responded more quickly at the expense of more errors.

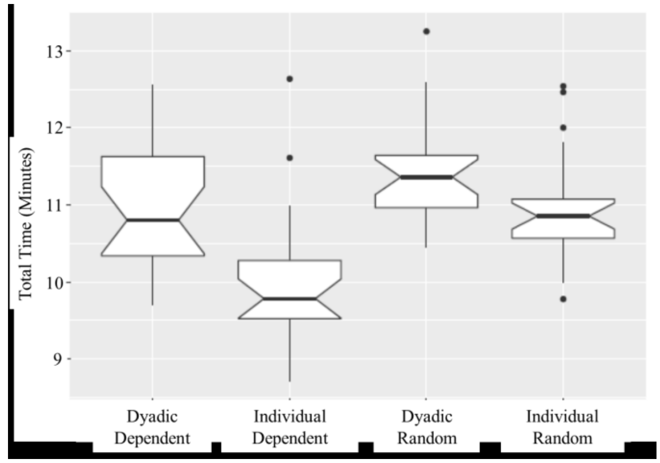

Figure 3. Mean time to complete the task as a function of Group Type and Movement Type.

Spectral Analysis

We used spectral analysis to measure temporal correlations in IRI time series, and also to measure the degree of matching between temporal correlations in response time fluctuations in the left and right hands (i.e. complexity matching). Temporal correlations are expressed as inverse relation between frequency and spectral power, and this relation can be quantified by fitting a second-order regression line to the power spectrum in log-log coordinates. The spectral function will closely follow a straight line in log-log coordinates if temporal correlations follow an inverse power law, or the function may bend away from a power law if random variations or short-range correlations are present. The slope of the linear coefficients of the regression line quantify temporal correlations across responses. More negative linear coefficients indicate stronger temporal correlations.

We conducted a 2 (Group Type—individual or dyad) X 2 (Movement Type—random or dependent) X 2 (Hand—right or left hand) mixed ANOVA on linear coefficients for each IRI spectrum produced by each hand in each block. The results indicated a significant main effect of Group Type, $F(1, 42) = 20.88$, $p < .001$, Movement Type, $F(1, 42) = 25.47$, $p < .001$, and Hand, $F(1, 42) = 6.90$, $p = .012$. There was also a significant two-way interaction between Movement Type and Hand, $F(1, 42) = 7.30$, $p = .01$. All other main effects and interactions were non-significant, $p > .05$. As can be seen in Figure 4, dyads had stronger temporal correlations than individuals did, and dependent drift caused stronger temporal correlations compared with random drift. Also, the right hand produced stronger temporal correlations than the left hand (not shown in the Figure 4).

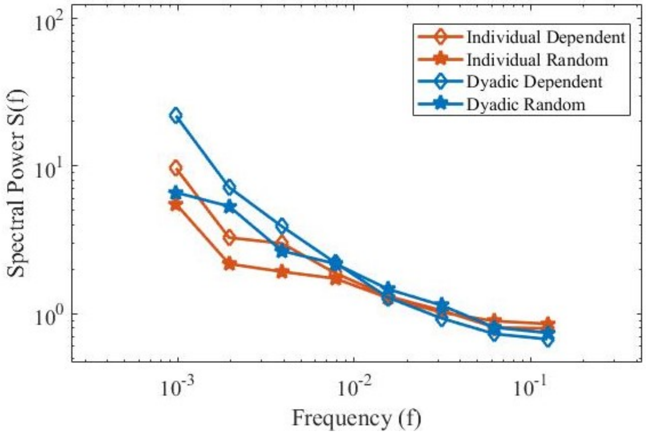

Figure 4. Spectral analysis: Group Type by Movement Type.

Complexity Matching

Next, we tested whether there was convergence in the temporal correlations produced by each hand, by testing the slopes of their respective spectra for each condition. There were significant and marginally significant positive correlation for the dyadic and individual dependent drift condition, respectively, but not for random drift: $r(22) = 0.38$, $p = .077$ for individuals (see Figure 5), and $r(22) = 0.57$, $p = .006$ for dyads (see Figure 6).

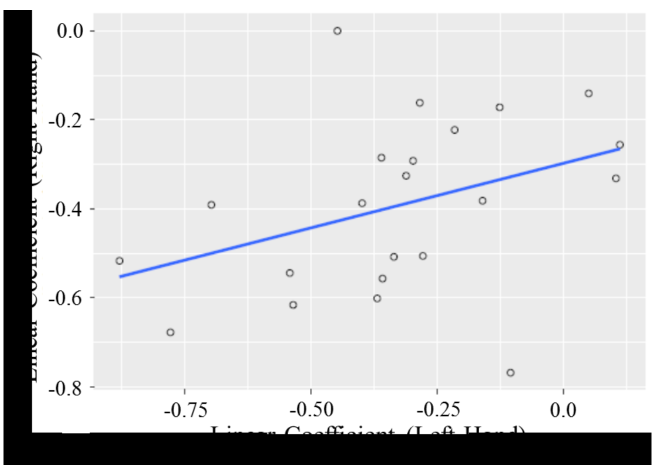

Figure 5: Individual Dependent Condition.

These correlations suggest that complexity matching occurred only when the hands coupled via interdependent target locations. Interestingly, the degree of complexity matching as measured by correlation coefficients was comparable for individuals and dyads, and absent when targets drifted randomly, even though the same individuals generated both responses.

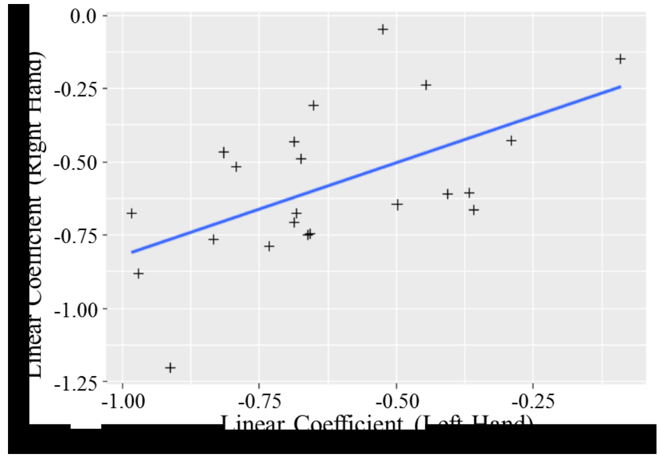

Figure 6: Dyadic Dependent Condition.

Discussion

The main goal of our experiment was to examine whether complexity matching is a general principle that applies similarly to coordination within and between individuals. Results showed that complexity matching occurred for both individuals and dyads, but only when responses were coupled via contingent drift in target positions. It is surprising and perhaps counterintuitive that complexity matching was extinguished by decoupling the left and right hand responses for individuals, even though the left and right hands were controlled by individual brains in this condition. It appears that response coupling is the critical factor in observing bimanual coordination, and not the fact that lateralized control of the left and right hands is coupled by the corpus callosum.

To put these results in context, we also found that individuals performed better overall compared with dyads, which indicates an advantage when one hand "has knowledge" of the other by virtue of being attached to the same brain—that is, when the left hand knows what the right hand is doing, so to speak. Nevertheless, this knowledge was not expressed as persistent complexity matching regardless of how targets drifted. Moreover, the better performance that this knowledge afforded also corresponded with weaker long-range correlations. In sum, complexity matching depended on coupling through the task itself, whereas performance and 1/f noise depended on the task as well as the system(s) performing the task.

The observed flexibility of bimanual coordination suggests that, akin to juggling, coordination in our experiment was *soft-assembled* (Kloos & Van Orden, 2009). Participants recruited the degrees of freedom available to accomplish the task, while also remaining available to re-organize into other coordinative configurations over time. Unified control over left and right-hand responses allowed individuals to coordinate differently from dyads, even though the task was otherwise the same across conditions. Dyads needed to communicate through response coupling, whereas individuals did not. Our results demonstrate that coupling strength in a bimanual coordination task does affect interpersonal coordination, as in Marmelat & Delignières (2012), and the strength of response coupling between individuals and dyads influenced measures of complexity matching.

A more complete examination of the link between coupling and complexity matching during bimanual coordination will require further analysis and experimentation. First, continuing to analysis the data using methods of non-linear statistics will help to clarify the way in which multiple limbs coordinate in space and time. Examining the relative phase relationship between the actions produced by individuals and dyads may reveal the underlying structure leading to the differing degrees of complexity matching observed in this task.

Additionally, another coupling condition could further our understanding of the dependent nature of coupling in coordinated behaviors. Variability in target locations was more predictable with dependent drift compared with random drift. Therefore, it is unclear whether the observed effects of dependent drift were due to the interactions between hands that created predictable target locations, or the predictability itself. We can test these competing hypotheses by testing a condition in which participants respond to targets whose locations are "played back" from a previously recorded block of dependent drift responses. If predictability is the underlying factor at play, then the playback condition should yield a similar pattern of results as the dependent drift condition. Alternatively, if collaborative interaction is the underlying factor, then the playback condition should be similar to the random drift condition.

Finally, further advances may come from further investigation into the conditions that manifest complementary coordination instead of simpler forms of coordination like synchrony and alignment. Other studies have found performance benefits from synchrony and alignment (van der Wel, Knoblich, & Sebanz, 2011), and understanding the principles and factors underlying these differing forms of coordination will help us know when it is time to swing to the beat together, or march to the beat of your own drum.

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