Dynamic Structure of Joint-Action Stimulus-Response Activity

MaryLauren Malone (malonemo@mail.uc.edu)
Center for Cognition, Action & Perception, University of Cincinnati, Cincinnati, OH, USA;

Ramon D Castillo (castilrn@mail.uc.edu)
Center for Cognition, Action & Perception, University of Cincinnati, Cincinnati, OH, USA;
Universidad de Talca, Chile

John G Holden (holdenjn@mail.uc.edu)
Center for Cognition, Action & Perception, University of Cincinnati, Cincinnati, OH, USA;

Heidi Kloos (heidi.kloos@uc.edu)
Center for Cognition, Action & Perception, University of Cincinnati, Cincinnati, OH, USA;

Michael J. Richardson (michael.richardson@uc.edu).
Center for Cognition, Action & Perception, University of Cincinnati, Cincinnati, OH, USA;

Abstract

The mere presence of a co-actor can influence an individual's response behavior. For instance, a social Simon effect has been observed when two individuals perform a Go/No-Go response to one of two stimuli in the presence of each other, but not when they perform the same task alone. Such effects are argued to provide evidence that individuals co-represent the task goals and the to-be-performed actions of a co-actor. Motivated by the complex-systems approach, the present study was designed to investigate an alternative hypothesis—that such joint-action effects are due to dynamical (time-evolving) entrainment processes that perturb and couple the behavior of socially situated actors. To investigate this possibility, participants performed a standard Go/No-Go Simon task in joint and individual conditions. The dynamic structure of recorded response times (RTs) was examined using fractal statistics and instantaneous cross-correlation. Consistent with our hypothesis that participants responding in a shared space would become behaviorally coupled, the analyses revealed that RTs in the joint condition displayed decreased fractal structure (indicative of an interpersonal coupling perturbing and constraining participant behavior) compared to the individual condition, and were more correlated across a range of time-scales compared to the RTs of pseudo-pair controls. Collectively, the findings imply that self-organizing dynamic processes might underlie social stimulus-response compatibility effects and shape joint cognitive processes in general.

Keywords: *joint action; stimulus-response compatibility; interpersonal coordination; pink noise; dynamical systems*

Introduction

Social interaction is a hallmark of everyday activity. Examples include a parent helping a child get dressed, a couple washing dishes together, people playing a team sport, or two workers carrying a heavy item up a flight of stairs. In each of these cases, a form of cooperation emerges such that the activity is coordinated across all participating actors. Interestingly, coordination emerges even when no explicit coordination is required, for example when people are completing separate parts of the task. The present study aims to further investigate this latter form of coordination.

Joint Stimulus-Response Compatibility (JSRC)

Over the past decade, a growing amount of research has been conducted investigating joint-action via so-called 'go/no-go tasks' (e.g., Sebanz, Knoblich, & Prinz, 2005; Sebanz, Bekkering, & Knoblich, 2006; Tsai, Kuo, Jing, Hung & Tzeng, 2006). In such tasks, participants are instructed to 'go' when given a certain stimulus context (e.g., when they are presented with a red stimulus), and to 'not go' when given the alternative (e.g. a blue stimulus image). The compatibility aspect of these experiments lies in the spatial orientation of the stimulus relative to the location of the responding individual. For instance, if a stimulus is presented on the same side of a display with respect to where a participant is seated, the response is deemed "compatible". Alternatively, if a stimulus is presented on the opposite side of a display screen with respect to where a participant is seated, the response is deemed "incompatible".

To examine the effects of such stimulus-response mappings in a joint-action setting, the reaction times (RTs) are compared between two conditions: one in which the participant sits on one side of the display screen and responds alone to one stimulus type (the individual condition), and another where the task requirements are exactly the same except that another participant, seated on the opposite side of the display screen, responds to the alternative stimulus (the joint condition). The general finding is that even though participants in the joint condition are performing the exact same task as in the individual condition, a greater SRC effect exists when two people are completing the task in one another's presence compared to

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when they complete the task alone. In other words, incompatible responses are significantly slower than compatible responses in joint conditions, but only marginally different (or not significantly different at all) for individual conditions.

These findings are generally taken as evidence for the co-representation of action goals during a joint-action setting, whereby actors form a shared representation of the collective task goal. That is, individuals mentally represent the actions of their co-actor and integrate them into their own action planning. This co-representation or action integration therefore results in slower RTs for incompatible stimulus situations compared to compatible stimulus situations. When completing the task alone, however, no such integration or co-representation occurs, and thus the spatial compatibility of the stimulus has little or no effect.

The JSRC effect has been observed across a wide range of stimulus and response manipulations, including hand posture (Cho, Proctor, & Yamaguchi, 2007), non-biological response mechanisms (Buhlmann, Umilta, & Wascher, 2007), orthogonality of stimulus location (Bae, Cho, & Proctor, 2009; Figliozzi, Silvetti, Rubichi, & Doricchi, 2010), and auditory stimuli (Buetti & Kerzel, 2008). It is also known to be influenced by various social psychological variables, such as the facial features of a co-actor, and task-sharing paradigms (Philipp & Prinz, 2010; Jung, Holländer, Müller, & Prinz, 2011).

JSRC effects also appear to suggest that knowing what another person's task is during joint-action is the means by which an individual can understand others' action intentions and points to *shared representations* as the casual basis of this integration or modulation process. A consequence of this co- or shared-representation and action integration emphasis, however, is that no research has attempted to examine the time-evolution or behavioral dynamics of actors' responses during JSRC tasks, nor the degree to which JSRC effects are a result of the dynamical entrainment or coordination processes that are known to exist during co-present joint-action situations (Richardson et al., 2012; Schmidt et al., 2011). The aims of the present study were therefore to (i) examine the dynamical structure of JSRC task behavior and (ii) investigate whether the standard (visual) JSRC effect might be a result of dynamic coordination or entrainment processes coupling the response behavior of co-acting individuals.

Examining the Dynamics of JSRC

At the crux of the traditional statistical analyses for JSRC experiments is a comparison of means, wherein each participant's time series of responses is represented as a single, unchanging number. The average RT response for each condition is understood as capturing the core and most meaningful aspect of the recorded RT behavior. The variability or time-evolution that occurs from trial-to-trial is simply discarded as error or mentioned only briefly in terms of how localized the mean is (for an exception see Vesper et al., 2011). The temporal structure of RT variability (i.e., deviations from the mean over time), however, often provides additional and meaningful information about how behavior emerges over time (Gilden, 2001). For instance, there is evidence that the seemingly error-induced variation in responses may actually be reflective of how people execute discrete motor responses in a certain spatiotemporal context (Wing & Kristofferson, 1973). Furthermore, even if the mean value and standard deviation are the same, the structure of RT time series that result in those means and standard deviations could in fact be quite different.

In order to examine the dynamic structure and unfolding variability of RTs over time, recent research has utilized fractal methods that provide deeper insight into the dynamics of an ongoing activity (Bassingthwaighte, Liebovitch, & West, 1994; Gilden, Thornton, & Mallon, 1995; Jensen, 1998; Van Orden, Holden, Turvey, 2003). Conceptually similar to geometric fractal patterns (Mandelbrot, 1982), fractal patterns in experimental time-series data correspond to nested patterns of variability found across repeatedly measured behaviors. Instead of comparing the overall means, fractal analysis involves determining how the variability exhibited in a time-series changes with changes in time-scale. That is, fractal analysis involves determining if the structure of variability in an RT time-series is statistically *self-similar* or *scale invariant*, such that small variations in the data have essentially the same structure as large variations (Brown & Liebovitch, 2010; West & Deering, 1995). As in geometrical fractal patterns, if one were to "zoom in" (i.e., examine a smaller scale) on the measurement time-series, one would discover essentially the same pattern of fluctuations evident at the larger scale (Holden, 2005). Accordingly, fractal statistical methods do not rely on partitioning the variability in measurement into different components, but rather assess the structure of the time-evolving variability observed.

A time-series containing random fluctuations (i.e., white noise) indicates that the observed variability is the result of unsystematic or unrelated changes from trial to trial (Van Orden, 2010). Alternatively, the variability in an RT time-series containing fractal or scale invariant structure contains trial-to-trial variability that is long-term correlated. In other words, the time-series contains nested patterns of variability wherein small variations in measurement have the same structure as large variations. Such structure in repeated measurements is often referred to as "pink noise" or $1/f$ noise and are characteristic of a wide range of naturally occurring complex (interaction-dominant) systems and phenomena, from eye movement patterns (Aks, Zelinsky, & Sprott, 2002) and heart rate variability (Eke et al., 2002), to self-reported mood change (Delignières, Fortes, & Ninot, 2004).

There are numerous methods for determining the degree to which the variability in a behavioral or response time-series is *scale invariant* or pink (see Delignières et al., 2006 for a review). One of the most robust methods is *detrended fluctuation analysis,* commonly referred to as

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DFA (Bassingthwaighte et al., 1994; Peng, Havlin, Stanley, & Goldberger, 1995). DFA quantifies the long-term correlative properties of behavior by detrending the time series of adjacent bins, or collections of consecutive data points, at all time scales. The residual variance obtained from the least-square regression line subtraction of each bin is calculated for progressively larger bin sizes. Bin size is plotted against variance on a log-log plot, and the scaling exponent, H, is revealed by the slope of the best-fitting line. For DFA, $H \approx 1.0$ indicates that the response variability or "noise" is pink (i.e., fractal). White noise, however, corresponds to $H = 0.5$.

Deviations away from 'perfect' pink noise (i.e., $H = 1.0$) can result from changes in system flexibility (Kloos & Van Orden, 2010). For instance, increasing task constraints or difficulty, such as coupling responses to external timers or events (i.e., metronomes), or increasing task speed, can whiten RT variability and result in $H \ll 1.0$ (Chen, Ding, & Kelso, 2001; Delignières et al., 2009; Hausdorff et al., 1996). Changes in H across conditions thus reveal how differing task manipulations result in processes that interact or constrain each other, as well as influence the overall organizational processes that underlie a series of behavioral responses (Van Orden, 2010). Accordingly, the question considered here was does the co-presence of an actor during a JSRC task change the fractal structure of an individual's RT behavior, and if so, how and why?

One possibility is that the behavior of individuals during joint-action conditions are subtly coupled or dynamically entrained and that this coupling or entrainment acts to constrain and/or perturb the behavioral responses of the individuals involved. There is a significant body of research demonstrating how the behaviors of co-present individuals often become dynamically coordinated or entrained (see Schmidt & Richardson, 2008; Marsh, Richardson, & Schmidt, 2009 for reviews) and that such processes can modulate and perturb individual behavior (Richardson et al., 2009, 2012; Riley, et al., 2011; Romero et al., 2012). If this is the case, then the fractal structure of the RT variability should be whiter in the joint condition compared to the individual condition.

To explore this possibility, we employed a standard SRC task, the Simon task (Craft & Simon, 1970), and had participants complete the task under joint and individual go/no-go conditions. We performed a fractal analysis on the resting RT time-series using DFA, with the expectation that the joint condition would exhibit a whiter fractal structure (H closer to 0.5) compared to RT time-series in the individual condition. In addition to performing a fractal analysis, we also employed *instantaneous cross-correlation* (Barbosa, Yehia, & Vatikiotis-Bateson, 2008) to index the degree to which the RTs of co-acting individuals were correlated (i.e., coordinated) with each other over time. If the behavioral responses of individuals are entrained during a joint-action situation, then the temporal correlation should be greater between the RT time series of individuals in the joint condition compared to RT time series of pseudo–pairs

created using RT time-series from participants who performed the task in the individual condition. We employed instantaneous cross-correlation because it allows one to determine how correlated two behavioral time-series are across multiple time-scales. The method is ideally suited for determining highly subtle non-synchronous coordination that occurs at variable time-lags. It essentially computes the correspondence between two signals recursively, generating a time-series of how past and future samples are correlated at all points in time. Setting a minimum r value as a cut-off for what is considered to be correlated or not (i.e., $r = .25$) then allows one to calculate the percentage of points that resulted in correlation values greater than that cutoff. The resultant value is the proportion of correlated activity and can be understood as providing a measure of percent coupling.

Methods

Participants
Twenty-four undergraduate students from the University of Cincinnati (7 male, 17 female) participated in the study. They ranged in age from 18 to 22 years old and received class credit for participation in the experiment.

Materials
A 19" Dell Flat Panel monitor was used to present stimuli. Stimuli included a blue "X" or red "X" (1" high, ½" wide), displayed on the left or right of the screen (positioned 5½" from the top and bottom of the screen, and 2" from the left or right side of the screen, respectively). Stimulus presentation and data collection was controlled using Direct RT. An Apple keyboard, modified to be millisecond accurate, was used to collect reaction time data. The shift keys were used as response indicators on the keyboard. A red sticker was placed on the right shift key and a blue sticker was placed on the left shift key. The monitor and the keyboard were placed in the center of a desk, with the keyboard 7" from the front of the desk and 8" from the monitor. Participants were seated in chairs that were placed next to each other in front of the keyboard. Each seated participant was positioned approximately 30" from the display screen.

Procedure
Participants completed a visual go/no-go Simon task in which they were instructed to respond with a key press to a specific stimulus color presented on the screen. Participants were assigned only one of the two stimulus colors (e.g. red) and were instructed to respond only to their designated color, regardless of location, while ignoring the alternative (e.g. blue). Participants completed the task in one of two experimental conditions: a joint condition or an individual condition. For the individual condition, participants performed the task alone. For the joint condition pairs of participants performed the task together. Similar to the procedure of Sebanz et al. (2003), subjects assigned to the

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red key sat on the right, and subjects assigned the blue key sat on the left, regardless of condition (see Figure 1). A brief instruction screen was presented on the computer monitor prior to the start of the experiment. Clarifying instructions were administered verbally and an opportunity for questions or clarification was offered.
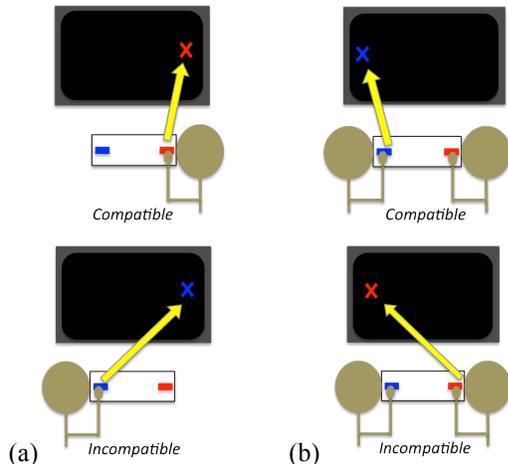

Figure 1: Experimental setup for (a) the individual condition, and (b) the joint condition.

Each trial began with a white crosshair presented for 400 ms in the center of the screen, followed by a blank screen also lasting 400 ms. Stimuli were presented for a maximum time of 1200 ms or until a response was indicated. Irrespective of RT, 400 ms of a blank screen was then presented 1200 ms after the stimulus presentation, followed by the white crosshair indicating the beginning of the next trial. In all conditions, participants completed 1100 trials, preceded by eight practice trials. An equal number of red and blue stimuli on both the left and right sides of the display were presented in a random order over the duration of the experiment.

Results
Analysis of Mean Reaction Time
A 2 (compatible vs. incompatible) × 2 (joint or individual experimental condition) mixed design ANOVA was conducted to determine whether the standard JSRC effect had occurred. Consistent with previous research (Sebanz et al., 2003; Sebanz et al., 2005), the analysis revealed a significant interaction between response compatibility and experimental condition, $F(2,22) = 5.86$, $p < .01$, with an effect of compatibility only being observed in the joint condition. This was confirmed using Bonferroni post hoc analyses, indicating that mean RTs were significantly faster for compatible responses ($M = 395$, $SD = 36$) than for incompatible responses ($M = 411$, $SD = 45$) in only the joint condition ($p < .05$). There was also a main effect of experimental condition, $F(2,22) = 26.99$, $p < .01$, with RTs in the joint condition ($M = 403$, $SD = 40$) being significantly faster than RTs in the individual condition ($M = 464$, $SD =$
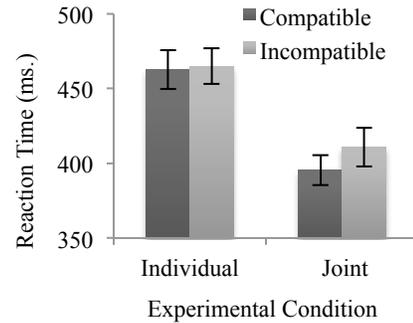
63).

Figure 2: Mean reaction time (RT) as a function of experimental condition and compatibility.

Fractal Analysis
DFA was performed on the last 512 responses for each participant. Prior to analysis, the RTs were normalized by subtracting the relevant condition means for each participant in order to examine the variability of the residual fluctuations (see Gilden, 2001 for a detailed description of the rationale). Consistent with our hypothesis that participants responding in the joint condition would exhibit a whiter fractal structure of responses due to task constraints and coupling, a between samples one tailed t-test performed on H values calculated using DFA revealed a significant effect of experimental condition, $t(22) = 2.25$, $p < .05$, with the fractal structure of RTs in the joint condition being significantly lower H ($M = 0.57$, $SD = 0.06$) than in the individual condition ($M = 0.63$, $SD = 0.08$) (see Figure 2). One sample t-tests indicated that H values were significantly different from a test value of 0.5 (hypothetical white noise) for both the individual, $t(11) = 5.93$, $p < .01$, and the joint conditions, $t(11) = 34.53$, $p < .01$.
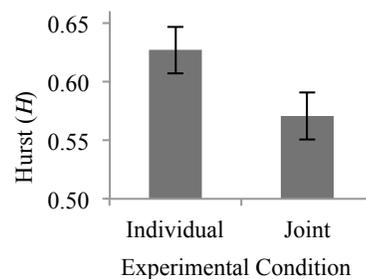

Figure 3: Mean Hurst *(H)* as a function of experimental condition.

Instantaneous Correlation
To determine the degree to which the RT time-series of participants in the joint condition were entrained or coupled to each other over time, we calculated the percentage of correlations within the time-series of instantaneous correlations for delays of -60 to 60 trials that had an $r > .25$. As mentioned above, the resultant value can be understood as a measure of percent coupling or the proportion of

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correlated activity. We then used a between samples one-tailed *t*-test to compare the percent coupling observed between participants in the joint condition to the percent coupling calculated between pseudo pairs of participants created by randomly pairing participants from the individual condition. Consistent with the hypothesis that the behavioral response of participants in the joint condition might be dynamically entrained or coupled, the analysis revealed that the percent coupling for the joint condition (%30.9) was (marginally) significantly greater, $t(22)= 1.65$, $p = .059$, compared to pseudo pairs (%21.6) created from participants in the individual condition (see Figure 3).
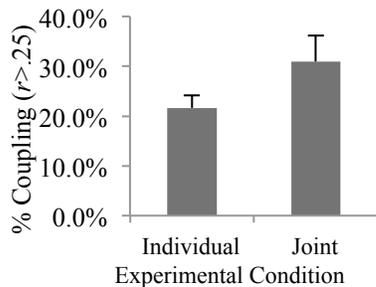

Figure 4: The percent coupling calculated using instantaneous cross correlation as a function of experimental condition.

Discussion

The experimental study present here was aimed at examining the behavioral dynamics of individuals during a joint-action stimulus-response compatibility task. We submitted recorded RT time-series during a JSRC task to both a standard comparison of means, and to various dynamical analysis methods in order to examine how RT variability evolved over time. We compared these patterns of variability between joint and individual conditions.

Consistent with previous research, we found a significant difference in the overall reaction times between the individual and joint conditions, as well as a significant compatibility effect in the joint condition. More importantly, by measuring the fractal structure of participants' RTs, we found that that the structure of variability in the joint condition was much whiter than in the individual condition, as predicted. The current results therefore extend previous research by demonstrating that the mere presence of another individual not only affects average RT, but also affects the dynamics of an individual's response behavior. This difference was theorized to be a consequence of the dynamical entrainment processes that mutually perturb and constrain the behavior of individuals in a shared environment (Schmidt & Richardson, 2008).

To further examine whether the response behaviors of participants were dynamically coupled, an instantaneous correlation analysis was performed. We compared the degree to which the RT behavior of pairs in the joint condition was correlated to the degree of RT correlations that occurred for pseudo pairs created from participants who completed the individual condition. The results of this analysis revealed that the response behavior of pairs in the joint condition exhibited greater temporal correlation compared to pseudo pairs, providing more evidence that the response behaviors of co-present individuals in the current go/no-go task were dynamically entrained. The magnitude of these temporal correlations was by no means large and occurred at non-synchronous time-lags. Thus, like most other forms of interpersonal entrainment or behavioral coupling (see e.g., Chartrand and Bargh, 1999; Schmidt & Richardson, 2008; for reviews), the entrainment that occurred was most likely intermittent, rather than constant, and did not occur synchronously or at any fixed time lag. The weak and complex nature of the interpersonal influence should not be discounted, however, given the fact that the mean differences in RT are also relatively small (as is typically the case JSRC studies). Indeed, the relative change in mean RT, fractal dimension (*H*), and % coupling are all somewhat equivalent.

In conclusion, the current study provides the first evidence that the response behavior of co-actors during a JSRC task is dynamically entrained and that such dynamical entrainment processes operate to constrain and perturb the time-evolving response variability of co-acting individuals. Although not directly tested here, it is possible that these dynamic processes of constraints and coupling may underlie the JSRC effect, rather than some form of shared representation. In truth, the dynamical systems and representational accounts of such behavior are not mutually exclusive and may in fact provide complementary explanations for such joint-action phenomena. Future research should be directed towards investigating these issues in order to better understand how the dynamics of joint-action activity shape joint cognitive processes.

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