Journal of Experimental Psychology: Human Perception and Performance

Movement Constraints on Interpersonal Coordination and Communication

Michael T. Tolston, Kevin Shockley, Michael A. Riley, and Michael J. Richardson

Online First Publication, July 21, 2014. http://dx.doi.org/10.1037/a0037473

Journal of Experimental Psychology:
Human Perception and Performance

0096-1523/14/$12.00 http://dx.doi.org/10.1037/a0037473

Movement Constraints on Interpersonal Coordination and Communication

Michael T. Tolston, Kevin Shockley, Michael A. Riley, and Michael J. Richardson
University of Cincinnati

The present study investigated how constraining movement affects interpersonal coordination and joint cognitive performance. Pairs of participants worked cooperatively to solve picture-puzzle tasks in which they conversed to identify differences between pictures in 3 degree-of-constraint conditions: both participants were free to move their hands (free-free; FF); both participants' hands were restrained (restrained-restrained; RR); and the hands of 1 participant were free while the hands of the other participant were restrained (free-restrained; FR). Eye tracking data were collected, and movement was measured at the waist, hand, and head. Data were analyzed using Cross-Recurrence Quantification Analysis (CRQ). Postural sway coordination, gaze coordination, and task performance were predicted to be highest in FF, followed by RR, and then by FR. Results showed the asymmetric FR condition generally exhibited lesser degrees of coordination than the symmetric Conditions FF and RR, and that the patterning of coordination in the symmetric conditions varied across the measured body segments. These results demonstrate that movement restraints affect not only interpersonal postural coordination, but also joint attention. Additionally, significant positive relationships were found between task performance and total amount of anterior-posterior movement measured at the head, hand and waist; number of utterances; and number of differences pairs found in the puzzles. These findings indicate a relationship between movement and task performance consistent with the hypotheses that both interpersonal coordination and cognitive performance are sensitive to local action constraints.

Keywords: interpersonal communication, movement coordination, gaze coordination, cross-recurrence quantification analysis, joint action

Embodied approaches to cognition (e.g., Clark, 1999; Shapiro, 2011) generally assume that the processes governing cognition and behavior are not solely a function of the brain, but emerge as interactions among cognition, action, and the environment (including the social environment). For example, being able to gesture freely has been linked to performance on a range of cognitive tasks, including memory (Cook, Mitchell, & Goldin-Meadow, 2008; Frick-Horbury & Guttentag, 1998; Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001; Morsella & Krauss, 2004), quantity of utterances (Morsella & Krauss, 2004), and content of utterances (Hostetter, Alibali, & Kita, 2007; Morsella & Krauss, 2004; Rauscher, Krauss, & Chen, 1996). Additionally, patterns of hand trajectories during cognitive tasks that require a movement to a response option have been linked to cognitive states (Freeman, Dale, & Farmer, 2011; McKinstry, Dale, & Spivey, 2008; Spivey, Grosjean, & Knoblich, 2005) and several studies have demonstrated an interaction between semantic processing and motor states (see Barsalou, 2008, for a review). Taken together, these findings implicate the motor system as a functional component in cognitive processes. Accordingly, including the motor system in the fundamental framework of these processes offers to lend insight into the constraints and underlying dynamics that govern cognition. In light of this possibility, Shockley, Richardson, and Dale (2009) hypothesized that the movement coordination that occurs spontaneously during conversation (e.g., Shockley, Santana, & Fowler, 2003) may be functionally linked to the cognitive coordination that is required for effective communication. We investigated this possibility by evaluating the relations between movement, interpersonal coordination, and communication.

When two individuals communicate they exhibit coordination in speech patterns and body movement (Condon & Ogston, 1967; Natale, 1975; Street, 1984). Coordination occurs both within and between the individuals. For instance, individuals are likely to gesture when they are speaking (Condon & Ogston, 1967; Kendon, 1970; Rimé, Schiaratura, Hupet, & Ghysselinckx, 1984), regardless of whether there is visual contact between themselves and a conversational partner (Alibali, Heath, & Myers, 2001; Bavelas, Gerwing, Sutton & Prevost, 2008). That phenomenon may reflect a relation between speech production and body movement termed *self-synchrony* (Condon & Ogston, 1967; Condon, 1988). Recently, it has also been found that simply engaging in a conversation with another person promotes coordination of postural sway patterns (Shockley et al., 2003; Stoffregen, Giveans, Villard, & Shockley, 2013; Stoffregen, Giveans, Villard, Yank, & Shockley, 2009), an outcome consistent with previous well-known findings of interpersonal coordination (e.g., Condon & Ogston, 1967; LaFrance, 1979; LaFrance, 1985; Newtson, Hairfield, Bloomingdale, & Cutino, 1987). However, the functional role of interpersonal coordination with respect to effective communication and

Michael T. Tolston, Kevin Shockley, Michael A. Riley, and Michael J. Richardson, Center for Cognition, Action, & Perception, Department of Psychology, University of Cincinnati.

This research was funded by National Science Foundation Grant BCS-0926662.

Correspondence concerning this article should be addressed to Michael T. Tolston, Department of Psychology, University of Cincinnati, Cincinnati, OH 45221. E-mail: tolstomt@mail.uc.edu

other measures of mutual cognitive alignment, such as joint attention (Sebanz, Bekkering, & Knoblich, 2006), has yet to be clearly identified.

In addition to body configurations, verbally interacting dyads also coordinate their gaze patterns. For example, Richardson and Dale (2005) demonstrated that patterns of gaze between speakers and listeners were significantly coordinated within a 3 s window, with a peak overlap of gaze occurring at 2 s. Additionally, the more tightly coupled the listener's gaze was to that of the speaker, the better the listener performed on a follow up questionnaire regarding the content of the speaker's monologue, showing an important link between gaze coordination and comprehension. Likewise, Richardson, Dale, & Kirkham (2007) demonstrated that when participants listened to the same background information pertaining to the object of their conversation their gaze patterns were more coordinated than when they did not listen to the same background, signifying that gaze-based measurements of joint attention are sensitive to cognitive factors. Additional research demonstrated that participants' beliefs play an important role in gaze coordination (Richardson, Dale, & Tomlinson, 2009), providing further evidence that measurable body states (e.g., gaze trajectories) are related to complex cognitive processes (e.g., state of belief) and that the sensitivity of these processes to the states of another person is important to communication. Together, these studies show that gaze-based measures of joint attention index effective communication and shared cognitive states. Given previous findings linking movement with cognition (Freeman et al., 2011; McKinstry et al., 2008; Spivey et al., 2005), the degree to which joint attention is captured by gaze coordination (Richardson & Dale, 2005) suggests a functional link between movement coordination and cognitive coordination that may be amenable to experimental manipulation. However, to our knowledge, there has been no study that has combined measurements of gaze coordination and interpersonal postural coordination, neither is there an account of the effects of changes in movement coordination on either shared attentional states or on communication.

The present study investigated the relation between movement, gaze coordination, and cognitive performance by examining the effects of restraining hand motion on both the degree of coordination within a conversational dyad and their performance on a joint cognitive task. Participants in the study completed a series of picture-puzzle tasks (cf. Richardson & Dale, 2005; Shockley et al., 2003) in one of three degree-of-constraint conditions: Either both participants were free to move their hands (free-free; FF; symmetric constraints), both participants had their hands restrained (restrained-restrained; RR; symmetric constraints), or one participant was free to move while the other had the hands restrained (FR; i.e., asymmetric constraints). Neither participant was made aware of the degree of constraint of his or her partner.

Given the sensitivity of postural sway trajectories to suprapostural tasks (Stoffregen, Pagulayan, Bardy, & Hettinger, 2000; Yardley, Gardner, Leadbetter, & Lavie, 1999) we anticipated that restraining hand movement would interfere with the interpersonal postural coordination that arises during conversation. Further, given that body movement has been shown to be related to cognition and communication, a disruption in bodily coordination may also influence cognitive coordination (i.e., communication), which may also be reflected in gaze coordination (one index of joint attention). In as much as shared attention is necessary for communication (Clark, 1996; Clark & Brennan, 1991), a decrease in gaze coordination should accompany a decrease in the effectiveness of communication (Richardson & Dale, 2005). Therefore, we predicted that postural coordination, gaze coordination, and task performance would all be similarly affected by degree-of-constraint, and that greater coordination and task performance would be found in the FF condition, followed by the RR condition. We expected to find the lowest degree of coordination and task performance in the FR condition, because of the asymmetry in possible gestural configurations.

Method

Participants

Forty participants (20 pairs) took part in this experiment. Eighteen were recruited from the University of Cincinnati Psychology Participation Pool, and two were recruited from fliers advertising a cash incentive of $5 per half hour. Two pairs failed to complete the task, and their data were discarded. All participants were required to have normal or corrected to normal vision and were screened for neurological and movement disorders, balance problems, motion sickness, allergies to latex and spandex, and for the presence of any recent injuries that impaired their ability to move or stand. Only individuals who spoke English as a primary language were permitted to take part in the study.

Materials and Apparatus

Motion data were collected using a magnetic motion tracking system (Polhemus Fastrak, Polhemus Corporation, Colchester, VT) at a frequency of 30 Hz (head data were collected at 60 Hz, but down-sampled to correspond to the collection frequency of waist and hand data). Gaze data were collected at 60 Hz using a head-mounted, near infrared eye-tracking system (EYE-TRAC 6 Head Mounted, Applied Science Laboratories, Bedford, MA) that combined eye movement with head movement from the motion tracking system to yield the gaze time series of each participant. Twelve pairs of color cartoon pictures printed on 61×69 cm poster board were used as stimuli. Stimuli were presented one at a time at approximately eye height and at a distance of 1.8 m from the participants.

Procedure

The University of Cincinnati Institutional Review Board approved all experimental protocols. Written informed consent was obtained from all participants before the experiment. After a briefing on the experimental procedure, participants entered a wooden framed cube ($1.98 \times 1.52 \times 2.44$ m) enclosed with walls on two opposing sides. Participants stood 1.8 m apart from each other with their feet shoulder width apart. Participants donned the eye-tracking headgear, to which a motion tracking sensor was rigidly affixed. An elastic strap with an attached motion tracking sensor was placed around the waist of each participant to track postural sway (cf. Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007; Shockley et al., 2003). Participants were also asked to wear a pair of thin running gloves, by which an affixed motion tracking sensor was secured to the right hand. Participants donned a tie-on waist apron with two large pockets in the front to provide a means for restraining hand motion. The eye trackers were then calibrated. After a successful calibration, an opaque curtain was drawn down the center of the chamber to visually isolate the participants from each other. Visual isolation was necessary to prevent participants from looking outside of the eye-tracking calibration area, which would result in unusable data. It also prevented participants from knowing of any asymmetry in the imposed constraints, which may have influenced communication patterns (e.g., Richardson et al., 2009).

Before beginning the first trial, one participant was randomly designated as Person 1 (the person whose hands were free in FR). Neither participant was informed of this designation. Before each trial, participants were informed of their individual degree-of-restraint condition via a 15.25 × 21.60 cm sign with instructions printed in 24 point font on the wall opposite of each participant, immediately below the puzzle stimulus. For those trials in which participants were to be restrained, the sign read “In this trial you are restrained. Please place your hands in your pockets,” whereas for the trials in which the participant was free to move, the sign read “In this trial you are free to move your hands. Please keep your hands out of your pockets.” Participants were told that their instructions may or may not change during the course of the experiment and that they should be mindful of which condition they are in at all times. Participants were also instructed to refrain from informing each other of their degree of restraint. Further, a visual confirmation in the form of a head nod indicating whether the instructions were understood was required from both participants before beginning each trial.

Participants worked together to solve a picture-puzzle task, in which each participant viewed one picture out of a complementary pair of pictures. The paired pictures were identical, with the exception of 10 small differences, and participants were tasked to find and enumerate these differences by describing the pictures to one another (see Figure 1). While the participants were solving the puzzles, the researchers kept track of the number of differences they found to index task performance.

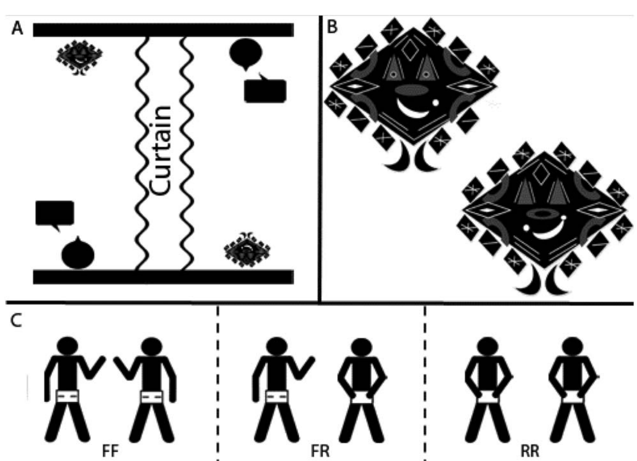

Figure 1. An overview of the method used in current experiment. (A) The relative positions of participants (represented by oval-shaped heads with triangular noses) in the data collection area. (B) An example pair of puzzle stimuli used during the experiment. (C) An illustration of the three degree-of-restraint conditions: free-free (FF), free-restrained (FR), and restrained-restrained (RR).

Design

Degree-of-constraint was manipulated as a within-subjects variable by placing upper extremity movement restrictions on Person 1 and on Person 2 (RR), on neither Person 1 nor on Person 2 (FF), or on Person 2 alone (FR). Pairs completed three trials in each of the three conditions (plus a single FF practice trial), for a total of 10 trials, each lasting 190 s. Trials were blocked by condition, the order of which was randomized separately for each pair, and the order of puzzles was completely randomized for each pair. The effects of restraining hand motion were assessed with respect to: total amount of anterior-posterior (AP)[1] displacement of the hand, head, and waist; interpersonal coordination; and task performance. For each measure, the resultant variables were averaged across the three trials per condition for each participant pair, yielding a single observation per pair in each condition. Because of time constraints that resulted from hardware complications, Pair 1 only performed two trials in the FR condition, whereas Pair 11 only performed two trials in each condition.

Following data preprocessing (see Appendix A), the postural sway time series and gaze-trajectory time series of participant pairs were submitted to *cross recurrence quantification* (CRQ) analysis, a nonlinear analysis method that allows one to compare how two time series evolve similarly over time (e.g., Richardson & Dale, 2005; Shockley et al., 2003). CRQ has been shown to be a sensitive measure of the degree of coupling between two systems (Shockley, Butwill, Zbilut, & Webber, 2002) as well as being a very robust statistical method that does not require that the data be stationary or conform to a particular distribution. CRQ was used to compute measures of the percentage of recurrent points (%REC), the number of shared data configurations relative to all possible configurations (a nonlinear measure similar to linear cross correlation); the percentage of deterministic points (%DET), the proportion of recurrent points that are part of a consecutive sequence of recurrent points (an index of the deterministic structure of the coordination); and the maximum diagonal line length (LMAX), the longest sequence of consecutively recurring points (a measure of how long the two people can maintain common movement trajectories, i.e., coordination stability). These measures quantified the magnitude and stability of both movement and gaze coordination between members of a conversational pair. Parameters for CRQ are discussed in Appendix B.

Before statistical analysis, the first and last 5 s of data from each trial were truncated to allow for task transition. Grubb’s outlier tests were then used to assess the data for outliers within each condition at the individual trial level, and again after the averages were calculated. Outliers in the latter level were handled in one of two ways: If there was only one outlier for a pair, that observation was replaced with the mean for the condition; if there were two or more outliers for a given pair, they were removed from that

[1] Movement along the AP axis was analyzed exclusively because it has been shown in previous studies to be sensitive to factors affecting conversational interaction (Shockley et al., 2003; Stoffregen et al., 2013; Stoffregen et al., 2009) and to reduce the number of dependent measures that would be obtained if medial-lateral sway were also analyzed.

analysis. For pair 15, the waist data for Person 2 was excessively noisy, possibly because of a faulty sensor or bad connection, and was thus discarded from analysis, though the other measures for that pair were retained. Task performance was indexed by tracking the number of differences found for each trial, and also by transcribing the recorded dialogue and summing the number of utterances per person per trial. Dependent measures that were defined across pairs (%REC, %DET, LMAX, and task performance) were submitted to one-way repeated-measures analyses of variance (ANOVA), whereas total movement and total utterances were submitted to two-way mixed AVOVAs with restraint as the within-subjects factor and person as the between-subjects factor. To test the experimental hypotheses, follow-up pairwise comparisons were planned between FF, FR, and RR for all measures. Pearson correlations were also calculated between task performance and the movement and gaze measures.

Results

Only analyses with statistically significant results are reported. In cases where homogeneity of variance was violated, a Greenhouse-Geisser correction was used.

Movement

Mean results for the effect of restraint on total AP hand displacement are shown in Figure 2. Although the aprons prevented large gestures, they did not restrict all hand movement, and some participants were observed moving their hands back and forth in the pockets while they were in the restrained condition. There was a main effect of restraint on total displacement, $F(2, 68) = 29.70$, $p < .001$, $\eta_p^2 = .466$. There was also a significant interaction between restraint and person, $F(2, 68) = 8.59$, $p < .001$, $\eta_p^2 = .202$. Main effect analyses showed that total AP hand displacement in FF was significantly higher than either FR [$t(35) = 2.05$, $p = .048$] or RR [$t(35) = 7.494$, $p < .001$]. This means that individuals on average moved their hands more in the free condition than in either the condition where one person was free or when both individuals had their hands restrained. Additionally, there was a significant difference in total AP hand displacement between FR and RR, $t(35) = 4.38$, $p < .001$, meaning that, on average, there was more hand movement when one person was restrained compared with when both participants had their hands restrained. Simple main effects showed a significant difference between amounts of total AP hand displacement for Person 1 and Person 2 in the FR condition, with Person 1 moving more than Person 2, $t(34) = 2.74$, $p = .01$. These results indicate that the manipulation achieved the intended result, in that the degree of hand movement was highest in FF and lowest in RR, with substantial differences between Person 1 and Person 2 only in the asymmetric condition.

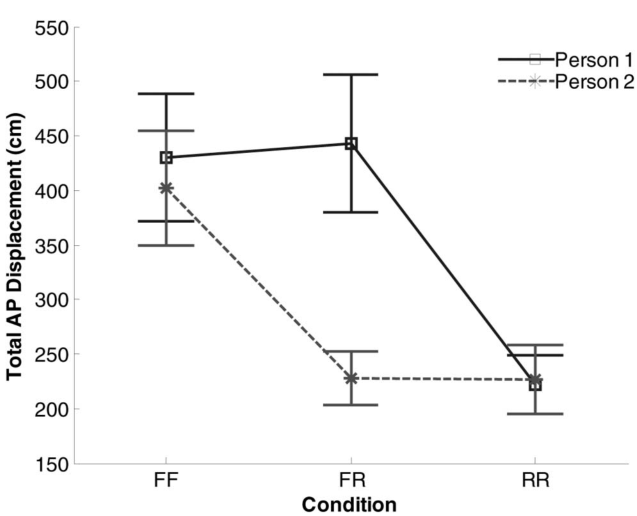

Figure 2. Mean values of total anterior-posterior (AP) displacement of the hand. Error bars represent ±1 *SE*.

Movement Coordination

Waist. The mean results for the effect of hand restraint[2] on %DET and LMAX at the waist are shown in Figure 3. Restraint had a significant effect on %DET, $F(2, 32) = 3.44$, $p = .044$, $\eta_p^2 = .177$, as well as on LMAX, $F(2, 32) = 5.18$, $p = .025$, $\eta_p^2 = .245$. Planned comparisons showed that %DET was significantly higher in RR than in FR, $p = .008$, meaning that the coordination was more deterministic when both individuals were restrained compared with when one was free and the other was restrained, whereas planned comparisons revealed that LMAX was significantly higher in FF than in FR, $p = .018$, and in RR than in FR, $p = .002$, meaning that the overall stability of coordination was higher when both individual's hands were free or restrained compared with when one individual's hands were free to move.

Head. The mean results for the effect of restraint on %REC and LMAX at the head are shown in Figure 4. Analyses revealed a significant effect of restraint on %REC, $F(2, 34) = 7.41$, $p = .007$, $\eta_p^2 = .304$, and also on LMAX, $F(2, 34) = 13.62$, $p = .001$. Planned comparisons showed that %REC was significantly higher in FF than in FR, $p = .003$, and also higher in RR than in FR, $p = .031$, meaning that there was a greater amount of overall coordination of the head between individuals when they could both move their hands or when they both had their hands restrained compared with when one person was restrained. Further planned analyses showed that LMAX was significantly higher in FF than in either FR, $p = .001$, or RR, $p = .001$, meaning that coordination patterns of movement of the head were more stable when both individuals could move compared with when they were both restrained or when one person was restrained and the other was free to move.

Gaze. The mean results for the effect of restraint on %REC, %DET, and LMAX are shown in Figure 5 Analysis of gaze overlap showed a significant main effect of restraint on %REC, $F(2, 32) = 4.89$, $p = .026$, $\eta_p^2 = .234$, with planned comparisons showing that %REC was significantly higher in FF compared with FR, $p = .026$. This means that there was a greater amount of gaze coordination when both participants could move their hands compared with when one was free and the other was restrained. Restraint also affected %DET, $F(2, 32) = 3.81$, $p = .033$. Planned comparisons showed a significantly higher %DET in FF than in

[2] As expected, hand restraint had a significant effect on all measures of hand coordination: %REC, $F(2, 34) = 11.78$, $p < .001$, $\eta_p^2 = .409$ (FF > FR, $p = .001$; FF > RR, $p = .002$), %DET, $F(2, 34) = 7.73$, $p = .002$, $\eta_p^2 = .313$ (RR > FF, $p = .02$), and LMAX, $F(2, 34) = 4.59$, $p = .017$, $\eta_p^2 = .213$ (FF > FR, $p = .016$).

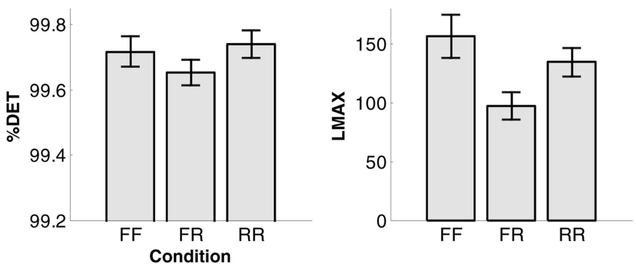

Figure 3. Mean values from CRQ analysis of waist data. Error bars represent ±1 *SE*.

FR (p = .025), meaning that the pattern of gaze coordination was more structured when both individuals were free to move their hands compared when only one person was free to move. LMAX was also significantly affected by restraint, $F(2, 32) = 6.21$, $p = .005$, $\eta_p^2 = .28$. Planned comparisons showed that LMAX was higher in FF compared with FR ($p = .011$), and also higher in RR compared with FR ($p = .015$), indicating that the overall stability of looking patterns was higher when both individuals were either free to move their hands or both had their hands restrained as compared with when one person's hands were restrained whereas the other person was free to move.

Task Performance

The mean results of the effects of restraint on task performance can be seen in Table 1. There were no significant effects of restraint on the number of differences participants identified. Correlations between task performance and other behavioral measures can be seen in Table 2. Significant correlations were found between the number of difference found and the number of utterances by Person 1 and the average number of utterances made by pairs. No such correlations were found between the utterances of Person 2 and differences found. Significant correlations were also found between the amount of total AP displacement of Person 1 at the hand, waist, and head, and differences found.

Discussion

This study examined the effect of restraining hand movement on interpersonal coordination and the task performance of dyads instructed to find differences in a series of picture puzzles via conversation. It was hypothesized that both coordination and task performance would be highest when both participants were free to move their hands (FF), followed by when both participants were both restrained (RR), and that both would be lowest when one participant was restrained and the other was free to move (FR). The results partially supported these hypotheses. Whenever there were significant differences in coordination patterns between conditions, the asymmetric FR condition generally exhibited lesser degrees of coordination. However, in the RR and FF conditions, the observed coordination patterns varied across body segments. Additionally, despite the fact that the restraint manipulation did not have a significant influence on task performance, correlations between task performance and the movement measures showed significant positive relations between movement, the number of utterances, and the number of differences found, consistent with our hypotheses. Further, the restraint manipulation did impact gaze coordination, evidencing the hypothesized link between bodily coordination and the coordination of attentional (cognitive) states.

Movement Coordination

The coordination of movements at both the waist and the head were affected by restraining hand motion. Because degree of restraint was shown to reduce the overall amount of hand movement, the observed effect on coordination measured at the waist is not surprising, given that postural sway is impacted by suprapostural tasks (Stoffregen et al., 2000; Yardley et al., 1999), including hand movement (Patla, Ishac, & Winter, 2002). We found that both the deterministic structure and the overall stability of coordination at the waist were higher in RR compared with FR. We also found that the overall stability of coordination at the waist was higher in FF compared with FR. For the head, the overall amount of coordination between individuals was higher in both FF and RR compared with FR. Additionally, coordination of head movement was more stable in FF compared with RR or FR. Together, these results show that similar constraints on movement and gesture (i.e., FF and RR) generally resulted in more stable and structured interpersonal coordination patterns than did dissimilar (FR) constraints.

Gaze Coordination

An asymmetry in movement constraint negatively impacted both the amount and the deterministic structure of shared looking patterns as compared with free movement. Furthermore, the overall stability of shared looking patterns was higher when movement was unrestrained. This means that not being able to move one's hands had a deleterious influence on joint attention. This complements findings in a previous study in which a manipulation of gaze coordination was shown to affect postural coordination (Stoffregen et al., 2013), demonstrating that suprapostrual tasks must be taken into account in evaluating conversational coordination, and that there is a bidirectional link between movement and gaze coordination. It remains, however, an open question as to whether a direct manipulation of gaze would similarly bring about different patterns of gesturing.

To summarize our results in terms of movement and gaze, we found that the spontaneous coordination of postural movements with another person was dependent upon conversants' ability to bring themselves into similar body configurations. This in itself is not surprising. What is particularly noteworthy, however, is that

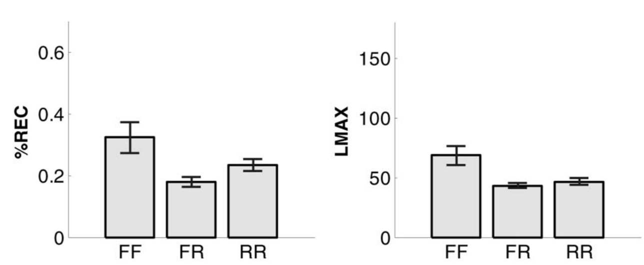

Figure 4. Mean values from CRQ analysis of head data. Error bars represent ±1 *SE*.

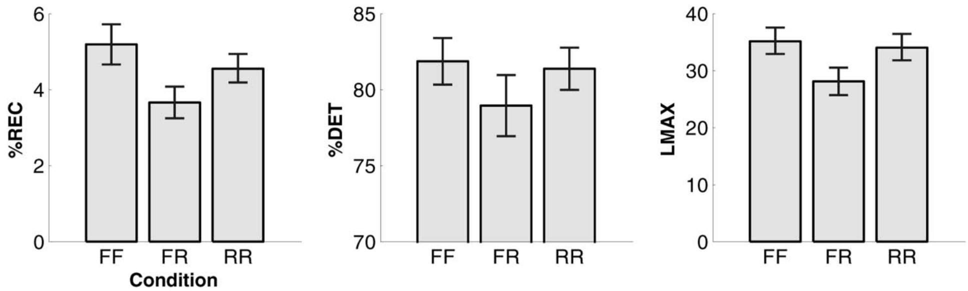

Figure 5. Mean values from CRQ analysis of gaze data. Error bars represent ±1 *SE*.

the change in degrees of freedom available to the separate individuals influenced gaze coordination, not simply in terms overlapping gazes, but in the structure of the time-dependent gaze patterns. We believe that such interactions across bodily and cognitive systems provide support for an embodied understanding of cognition (Van Orden, Kloos, & Wallot, 2011).

Relationships Among Movement, Coordination, and Communication

Contrary to our hypothesis, we found that task performance was not affected by the degree of constraint factor, which suggests three possible interpretations. First, it is possible that bodily coordination is an incidental, nonfunctional artifact of conversation. We find this explanation unlikely for at least two reasons. First, postural coordination observed during conversation is affected by conversational partner (Shockley et al., 2003)—it does not spontaneously arise when copresent agents are talking but not to each other. Second, there is a social element involved in spontaneous coordination of postural sway brought about by coordinated speech production (Shockley, Baker, Richardson, & Fowler, 2007). Both of these findings suggest a functional, rather than an incidental, role.

Second, it is possible that the measure of task performance was too coarse of a measure of cognitive alignment; Only 10 possible differences in each puzzle may not offer enough resolution in terms of differentiating subtle performance changes. This interpretation is supported by the fact that gaze coordination, a known measure of shared attentional states, was affected by the restraint manipulation, suggesting that more sensitive measures might reveal patterns of communication that are functionally related to movement coordination. It should be noted that we have no evidence that the puzzles were too easy, because it would then be expected that many pairs would find most of the differences in the puzzles, which was not the case. On average they found 5.84 differences (with a range of 2 to 10).

Third, it may be the case that the functional role of coordination in communication is not a strictly linear relation, but rather a more complex interaction. One possible explanation for this is the postulated role of symmetry formation and symmetry breaking in movement patterns and the exchange of information (Ashenfelter, Boker, Waddell, & Vitanov, 2009; Boker & Rotondo, 2002; Pickering & Garrod, 2004). According to the interactive alignment model, when individuals share bodily configurations, they are actually priming their perceptual systems to perceive the world in similar ways, therefore, facilitating an implicit mutual understanding of a shared environment (Pickering & Garrod, 2004). This alignment would be expected to result in greater degrees of bodily coordination, as was predicted by the hypothesis of this experiment. However, once alignment has been reached and individuals share a common perspective, the asymmetries that remain may represent information available to one person that is hidden from the other. To share this information, the alignment must be broken and asymmetry introduced into the relationship, which, according to an embodiment perspective, would indicate a break in the higher-order coordination pattern existing between the two individuals, which at the same time provides context for new alignment. Thus, although it is important to coordinate movement to reach a common understanding, for some tasks it may be equally important to break this coordination. It could, therefore, be expected that the formation and breaking of coordinative patterns would offset each other, obscuring results when coordination patterns are assessed across entire trials with respect to task performance.

A specific test of such an influence of postural coordination on communication would be to have participants engage in the conversational task described here, but under varying degrees of

Table 1
Task Performance by Condition

	M (*SD*)		
Measure of task performance	FF	FR	RR
Differences found	5.64 (0.93)	5.88 (1.14)	6.00 (0.98)
Utterances Person 1	285.07 (75.17)	279.22 (81.99)	285.31 (66.18)
Utterances Person 2	252.20 (77.25)	260.83 (76.52)	251.30 (71.45)
Mean utterances of pair	266.74 (77.39)	268.69 (78.89)	266.34 (70.55)

Table 2
Correlations of Task Performance Variables With Behavioral Measures

	A			B			AB			Diff		
	r	*p*	*N*	*r*	*p*	*N*	*r*	*p*	*N*	*r*	*p*	*N*
A				−0.34	.01	54	0.57	.00	54	0.29	.03	54
B	−0.34	.01	54				0.58	.00	54	—	—	—
AB	0.57	.00	54	0.58	.00	54				0.28	.04	54
%DET Hand	—	—	—	—	—	—	−0.38	.01	52	—	—	—
%DET JWG	−0.36	.01	49	—	—	—	—	—	—	—	—	—
DIFF	0.29	.03	54	—	—	—	0.28	.04	54	—	—	—
DMAX Gaze	−0.33	.02	50	—	—	—	—	—	—	—	—	—
DMEAN Gaze	−0.35	.01	50	—	—	—	—	—	—	—	—	—
DMEAN Head	—	—	—	—	—	—	−0.27	.04	54	—	—	—
Hand P1	0.27	.05	54	0.29	.03	54	0.49	.00	54	0.32	.02	54
Head P1	0.27	.05	54	—	—	—	0.45	.00	54	0.40	.00	54
Head P2	—	—	—	0.41	.00	54	—	—	—	—	—	—
LMAX Hand	−0.29	.04	54	—	—	—	—	—	—	—	—	—
%REC JHG	—	—	—	0.28	.04	51	—	—	—	—	—	—
Waist P1	—	—	—	—	—	—	—	—	—	0.36	.01	51

Note. Only statistically significant results are reported. A = number of utterances, P1; B = number of utterances, P2; AB = mean number of utterances, P1 and P2; JWG = JRQ Waist-Gaze; Diff = number of differences found in picture puzzles; DMAX = maximum distance of any two points in phase space; DMEAN = mean distance between all points in phase space; Hand P1 = total AP displacement of Person 1's hand; Head P1 = total AP displacement of Person 1's head; Head P2 = total AP displacement of Person 2's head; JHG = JRQ Head-Gaze.

structured coordinative modes. For example, it would be possible to have participants sway in varying phase relations to one another while performing the task. By establishing fixed states of coordination of varying stability, the symmetry breaking hypotheses could be tested in that deviations from imposed and otherwise stable coordination modes (such as in-phase synchrony; Haken, Kelso, & Bunz, 1985) would, by hypothesis, evidence the required symmetry breaking for the task imperative of communication. If symmetry breaking is a prerequisite for information exchange (Ashenfelter et al., 2009), then breaking of the symmetric postural phase constraints would be necessary during communication, resulting in an increase in phase variability with respect to the imposed frequencies. If, however, a postural phase relation is established that is asymmetric, individuals may still be able to maintain their requisite coordination modes while exchanging information. Relatively less stable phase relations (e.g., irrational phase relations; Treffner & Turvey, 1993) might, therefore, be expected to be more conducive to communication compared with relations that are highly stable. This pattern of results would suggest that communication constraints may result in distributions of coordinative modes that are qualitatively different than those that arise in a similar task that imposes only visual constraints, given that previous research has demonstrated an influence of visual coupling on spontaneous interpersonal coordination on postural sway in an upright stance in the direction of stable modes (e.g., in-phase coordination, Varlet, Marin, Lagarde, & Bardy, 2011). It should be noted that the proposed method is a slightly alternative formulation of the embodiment hypothesis compared with frameworks that suggest a nonarbitrary relation between body configurations and mental states (Barsalou, 2008; Niedenthal, 2007). Namely, any influence on communication in the proposed experiment would arise from the relative timing of configurations that may disrupt or facilitate entrainment (Clayton, Sager, & Will, 2004; Gill, 2012), rather than the particular form that the configurations take.

Lastly, with respect to task performance, we found significant relations between speech, movement, coordination, and task performance. Total AP displacement of the hand, waist, and head of those individuals randomly designated as Person 1 (those free to gesture in asymmetric restraint conditions) were positively correlated with the number of differences found, as were the total number of utterances made by Person 1 and by the dyad on average. The overall movement and number of utterances of Person 2 were not correlated significantly with task performance. Though this asymmetry in relationships is consistent with the asymmetry in restraints placed on the two individuals, it is possible that having Person 2 restrained in two out of three conditions created a subtle carry-over effect that somehow affected movement in the FF condition. However, the fact that there were no differences in the overall amount of hand displacement between Person 1 and Person 2 in either the FF or the RR conditions (see Figure 2) is evidence against this. Also noteworthy is that the number of utterances made by Person 2 positively correlated with the amount of hand motion made by Person 1, potentially reflecting the interactional synchrony—movement of one person in synchrony with the speech of another—that has been observed in previous studies (Condon & Ogston, 1971; Newtson, 1994).

Although there has been considerable research on the role of gesture in communication, most studies have looked at either gesturing during specific communicative roles (Hoetjes, Krahmer, & Swerts, 2014; Lickiss & Wellens, 1978), the effect of visibility of the conversational partner on the amount of gesturing and speech production (Alibali et al., 2001; Bavelas et al., 2008), or have not documented a relation between gesturing and effective communication and shared attentional states (Rimé et al., 1984). By combining measurements and methods shown to objectively quantify coordination and joint attention, we were able to investigate the relation between gesture, communication, and joint attention. By creating an asymmetry between the individuals' action capabilities, we were able to evaluate the effects of having access to qualitatively different behavioral modes on coordination and the subsequent effect on cognitive measurements of joint attention and task performance.

In summary, constraining hand movement within conversing dyads affected the coordination patterns between individuals measured at the head, waist, and gaze, showing that local constraints placed on subunits of the action system affect interpersonal coordination across different levels of observation. Particularly, body and gaze coordination patterns were attenuated in the FR condition, demonstrating a destabilizing effect of asymmetric movement across the coordination of ostensibly independent subsystems. Specifically, the deleterious effect of asymmetric constraints of hand movement on gaze coordination, an index of joint attention (Richardson & Dale, 2005; Richardson et al., 2007), shows that constraining the action system influences cognitive coordination, a finding in line with an embodied understanding of cognition. Further, cognitive performance, in terms of number of utterances and number of differences found, was shown to be significantly correlated with movement, demonstrating a link between action and joint cognitive performance that is also consistent with an embodiment viewpoint.

Acknowledgment

This research was funded by National Science Foundation grant BCS-0926662.

References

Abarbanel, H. D. I. (1996). *Analysis of observed chaotic data*. New York, NY: Springer-Verlag. doi:10.1007/978-1-4612-0763-4

Alibali, M. W., Heath, D. C., & Myers, H. J. (2001). Effects of visibility between speaker and listener on gesture production: Some gestures are meant to be seen. *Journal of Memory and Language, 44,* 169–188. doi:10.1006/jmla.2000.2752

Ashenfelter, K. T., Boker, S. M., Waddell, J. R., & Vitanov, N. (2009). Spatiotemporal symmetry and multifractal structure of head movements during dyadic conversation. *Journal of Experimental Psychology: Human Perception and Performance, 35,* 1072–1091. doi:10.1037/a0015017

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology, 59,* 617–645. doi:10.1146/annurev.psych.59.103006.093639

Bavelas, J., Gerwing, J., Sutton, C., & Prevost, D. (2008). Gesturing on the telephone: Independent effects of dialogue and visibility. *Journal of Memory and Language, 58,* 495–520. doi:10.1016/j.jml.2007.02.004

Boker, S. M., & Rotondo, J. L. (2002). Symmetry building and symmetry breaking in synchronized movement. In M. Stamenov & V. Gallese (Eds.), *Mirror neurons and the evolution of brain and language* (pp. 163–171). Philadelphia, PA: John Benjamins Publishing Company. doi:10.1075/aicr.42.14bok

Clark, A. (1999). An embodied cognitive science? *Trends in Cognitive Sciences, 3,* 345–351. doi:10.1016/S1364-6613(99)01361-3

Clark, H. H. (1996).*Using language*. Cambridge: Cambridge University Press. doi:10.1017/CBO9780511620539

Clark, H. H., & Brennan, S. E. (1991). Grounding in communication. In L. B. Resnick, J. M. Levine, & S. D. Teasley (Eds.), *Perspectives on socially shared cognition* (pp. 127–149). Washington, DC: American Psychological Association. doi:10.1037/10096-006

Clayton, M., Sager, R., & Will, U. (2004). In time with the music: The concept of entrainment and its significance for ethnomusicology. *ESEM Counterpoint, 1,* 1–82.

Condon, W. S. (1988). An analysis of behavioral organization. *Sign Language Studies, 58,* 55–88. doi:10.1353/sls.1988.0007

Condon, W. S., & Ogston, W. D. (1967). A segmentation of behavior. *Journal of Psychiatric Research, 5,* 221–235. doi:10.1016/0022-3956(67)90004-0

Condon, W., & Ogston, W. (1971). Speech and body motion synchrony of the speaker-hearer. In D. Horton & J. Jenkins (Eds.), *The perception of language* (pp. 150–184). Columbus, OH: Merrill.

Cook, S. W., Mitchell, Z., & Goldin-Meadow, S. (2008). Gesturing makes learning last. *Cognition, 106,* 1047–1058. doi:10.1016/j.cognition.2007.04.010

Duchowski, A. T. (2007). *Eye tracking methodology: Theory and practice*. New York, NY: Springer-Verlag.

Freeman, J. B., Dale, R., & Farmer, T. A. (2011). Hand in motion reveals mind in motion. *Frontiers in Psychology, 2,* 59. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3110497/

Frick-Horbury, D., & Guttentag, R. E. (1998). The effects of restricting hand gesture production on lexical retrieval and free recall. *The American Journal of Psychology, 111,* 43–62. doi:10.2307/1423536

Gill, S. P. (2012). Rhythmic synchrony and mediated interaction: Towards a framework of rhythm in embodied interaction. *AI & Society, 27,* 111–127. doi:10.1007/s00146-011-0362-2

Goldin-Meadow, S., Nusbaum, H., Kelly, S. D., & Wagner, S. (2001). Explaining math: Gesturing lightens the load. *Psychological Science, 12,* 516–522. doi:10.1111/1467-9280.00395

Haken, H., Kelso, J. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics, 51,* 347–356. doi:10.1007/BF00336922

Hoetjes, M., Krahmer, E., & Swerts, M. (2014). Does our speech change when we cannot gesture? *Speech Communication, 57,* 257–267. doi:10.1016/j.specom.2013.06.007

Hostetter, A. B., Alibali, M. W., & Kita, S. (2007). *Does sitting on your hands make you bite your tongue? The effects of gesture prohibition on speech during motor descriptions*. In *Proceedings of the 29th Annual Meeting of the Cognitive Science Society* (pp. 1097–1102). Mawhah, NJ: Erlbaum.

Kendon, A. (1970). Movement coordination in social interaction: Some examples described. *Acta Psychologica, 32,* 101–125. doi:10.1016/0001-6918(70)90094-6

LaFrance, M. (1979). Nonverbal synchrony and rapport: Analysis by the cross-lag panel technique. *Social Psychology Quarterly, 42,* 66–70. doi:10.2307/3033875

LaFrance, M. (1985). Postural mirroring and intergroup relations. *Personality and Social Psychology Bulletin, 11,* 207–217. doi:10.1177/0146167285112008

Lickiss, K. P., & Wellens, A. R. (1978). Effects of visual accessibility and hand restraint on fluency of gesticulator and effectiveness of message. *Perceptual and Motor Skills, 46,* 925–926. doi:10.2466/pms.1978.46.3.925

McKinstry, C., Dale, R., & Spivey, M. J. (2008). Action dynamics reveal parallel competition in decision making. *Psychological Science, 19,* 22–24. doi:10.1111/j.1467-9280.2008.02041.x

Morsella, E., & Krauss, R. M. (2004). The role of gestures in spatial working memory and speech. *The American Journal of Psychology, 117,* 411–424. doi:10.2307/4149008

Natale, M. (1975). Social desirability as related to convergence of temporal speech patterns. *Perceptual and Motor Skills, 40,* 827–830. doi:10.2466/pms.1975.40.3.827

Newtson, D. (1994). The perception and coupling of behavior waves. In R. R. Vallacher & A. Nowak (Eds.), *Dynamical systems in social psychology* (pp. 139–167). New York, NY: Academic.

Newtson, D., Hairfield, J., Bloomingdale, J., & Cutino, S. (1987). The structure of action and interaction. *Social Cognition, 5,* 191–237. doi:10.1521/soco.1987.5.3.191

Niedenthal, P. M. (2007). Embodying emotion. *Science, 316,* 1002–1005. doi:10.1126/science.1136930

Patla, A. E., Ishac, M. G., & Winter, D. A. (2002). Anticipatory control of center of mass and joint stability during voluntary arm movement from a standing posture: Interplay between active and passive control. *Experimental Brain Research, 143,* 318–327. doi:10.1007/s00221-001-0968-6

Pickering, M. J., & Garrod, S. (2004). Toward a mechanistic psychology of dialogue. *Behavioral and Brain Sciences, 27,* 169–190. doi:10.1017/S0140525X04000056

Rauscher, F. H., Krauss, R. M., & Chen, Y. (1996). Gesture, speech, and lexical access: The role of lexical movements in speech production. *Psychological Science, 7,* 226–231. doi:10.1111/j.1467-9280.1996.tb00364.x

Richardson, D. C., & Dale, R. (2005). Looking to understand: The coupling between speakers' and listeners' eye movements and its relationship to discourse comprehension. *Cognitive Science, 29,* 1045–1060. doi:10.1207/s15516709cog0000_29

Richardson, D. C., Dale, R., & Kirkham, N. Z. (2007). The art of conversation is coordination. *Psychological Science, 18,* 407–413. doi:10.1111/j.1467-9280.2007.01914.x

Richardson, D. C., Dale, R., & Tomlinson, J. M. (2009). Conversation, gaze coordination, and beliefs about visual context. *Cognitive Science, 33,* 1468–1482. doi:10.1111/j.1551-6709.2009.01057.x

Richardson, M. J., Marsh, K. L., Isenhower, R. W., Goodman, J. R., & Schmidt, R. C. (2007). Rocking together: Dynamics of intentional and unintentional interpersonal coordination. *Human Movement Science, 26,* 867–891. doi:10.1016/j.humov.2007.07.002

Riley, M. A., Balasubramaniam, R., & Turvey, M. T. (1999). Recurrence quantification analysis of postural fluctuations. *Gait & Posture, 9,* 65–78. doi:10.1016/S0966-6362(98)00044-7

Rimé, B., Schiaratura, L., Hupet, M., & Ghysselinckx, A. (1984). Effects of relative immobilization on the speaker's nonverbal behavior and on the dialogue imagery level. *Motivation and Emotion, 8,* 311–325. doi:10.1007/BF00991870

Salvucci, D. D., & Goldberg, J. H. (2000). Identifying fixations and saccades in eye-tracking protocols. *Proceedings of the 2000 symposium on eye tracking research & applications* (pp. 71–78). New York, NY: ACM Press.

Sebanz, N., Bekkering, H., & Knoblich, G. (2006). Joint action: Bodies and minds moving together. *Trends in Cognitive Sciences, 10,* 70–76. doi:10.1016/j.tics.2005.12.009

Shapiro, L. A. (2011). *Embodied cognition*. New York, NY: Taylor & Francis.

Shockley, K. (2005). Cross recurrence quantification of interpersonal postural activity. In M. A. Riley & G. C. Van Orden (Eds.), *Tutorials in contemporary nonlinear methods for the behavioral sciences* (pp. 142–177). Retrieved from http://www.nsf.gov/sbe/bcs/pac/nmbs/nmbs.jsp

Shockley, K., Baker, A. A., Richardson, M. J., & Fowler, C. A. (2007). Articulatory constraints on interpersonal postural coordination. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 201–208. doi:10.1037/0096-1523.33.1.201

Shockley, K., Butwill, M., Zbilut, J. P., & Webber, C. L. (2002). Cross recurrence quantification of coupled oscillators. *Physics Letters A, 305,* 59–69. doi:10.1016/S0375-9601(02)01411-1

Shockley, K., Richardson, D. C., & Dale, R. (2009). Conversation and coordinative structures. *Topics in Cognitive Science, 1,* 305–319. doi:10.1111/j.1756-8765.2009.01021.x

Shockley, K., Santana, M.-V., & Fowler, C. A. (2003). Mutual interpersonal postural constraints are involved in cooperative conversation. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 326–332. doi:10.1037/0096-1523.29.2.326

Spivey, M. J., Grosjean, M., & Knoblich, G. (2005). Continuous attraction toward phonological competitors. *Proceedings of the National Academy of Sciences of the United States of America, 102,* 10393–10398. doi:10.1073/pnas.0503903102

Stoffregen, T. A., Giveans, M. R., Villard, S. J., & Shockley, K. (2013). Effects of visual tasks and conversational partner on personal and interpersonal postural activity. *Ecological Psychology, 25,* 103–130. doi:10.1080/10407413.2013.753806

Stoffregen, T. A., Giveans, M. R., Villard, S., Yank, J. R., & Shockley, K. (2009). Interpersonal postural coordination on rigid and non-rigid surfaces. *Motor Control, 13,* 471–483.

Stoffregen, T. A., Pagulayan, R. J., Bardy, B. G., & Hettinger, L. J. (2000). Modulating postural control to facilitate visual performance. *Human Movement Science, 19,* 203–220. doi:10.1016/S0167-9457(00)00009-9

Street, R. L., Jr. (1984). Speech convergence and speech evaluation in fact-finding interviews. *Human Communication Research, 11,* 139–169. doi:10.1111/j.1468-2958.1984.tb00043.x

Treffner, P. J., & Turvey, M. T. (1993). Resonance constraints on rhythmic movement. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 1221–1237. doi:10.1037/0096-1523.19.6.1221

Van Orden, G., Kloos, H., & Wallot, S. (2011). Living in the pink: Intentionality, wellness, and complexity. In C. Hooker (Ed.), *Handbook of the philosophy of science, volume 10*: *Philosophy of complex systems* (pp. 629–672). Oxford: New Holland.

Varlet, M., Marin, L., Lagarde, J., & Bardy, B. G. (2011). Social postural coordination. *Journal of Experimental Psychology: Human Perception and Performance, 37,* 473–483. doi:10.1037/a0020552

Webber, C. L. (2005). Recurrence quantification analysis of nonlinear dynamical systems. In M. A. Riley & G. C. Van Orden (Eds.), *Tutorials in contemporary nonlinear methods for the behavioral sciences* (pp. 26–94). Retrieved from http://www.nsf.gov/sbe/bcs/pac/nmbs/nmbs.jsp

Winter, D. (2005). *Biomechanics and motor control of human movement*. Hoboken, NJ: J. Wiley and Sons.

Yardley, L., Gardner, M., Leadbetter, A., & Lavie, N. (1999). Effect of articulatory and mental tasks on postural control. *Neuroreport, 10,* 215–219. doi:10.1097/00001756-199902050-00003

(*Appendices follow*)

Appendix A

Data Processing and Reduction

Movement Data

All reported movement data are along the anterior-posterior (AP) axis. Before analysis, movement signals from the waist, hand, and head were filtered using a second-order high-pass Butterworth filter. Selection of a filtering parameter was achieved through residual analysis (Winter, 2005) by taking the square root of the sum of the squared differences between the raw signal and filtered signals across a range of filter cutoff frequencies and choosing a parameter setting that yields an average residual above the noise inherent in the measurement, such that

$$R(f_c) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \hat{x}_i)^2}, \tag{A1}$$

where R is the residual of the filtered data at a given cutoff frequency f_c, N is the number of samples, x_i is the unfiltered data at sample i, and $\hat{x}_i$ is the filtered data at sample i. Because the residuals of a signal consisting of pure noise would be an approximately straight line decreasing from 0 Hz on the y-axis to the Nyquist frequency on the x-axis, the asymptotic line of the residual represents a best guess as to the amount of noise in the signal. Thus, to calculate the filtering frequency for a given sensor, a least-squares line was fit to the residual asymptote for each observed signal (see Figure A1), and the filtering frequency with a residual equal to the intercept of this line was recorded. This was repeated for each signal, and the filtering frequency used in the analysis was the average of these values. This resulted in a chosen filtering frequency of 2.67 Hz for the waist (SD = 0.51), 3.03 Hz for the hand (SD = 1.11), and 3.66 Hz for the head (SD = 0.55).

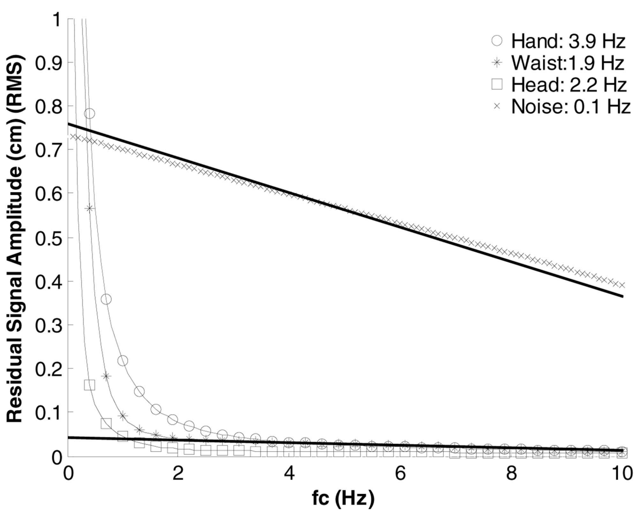

Figure A1. Residual analysis for a range of cut-off frequencies (fc). Illustrated residuals were calculated from the hand, waist, and head sensors taken from one individual in a single trial, as well as a random signal, with the least-squares-fit line to the asymptote of residuals for the waist and random data (noise) plotted as solid lines. The variable location at which the residuals equal the intercept of the least-squares line demonstrates different movement frequencies of the various body segments. The residual for the random signal is plotted to as a proof of concept, and it should be noted that the recommended filtering frequency is equal to the first minimum-step interval used in calculating the residuals.

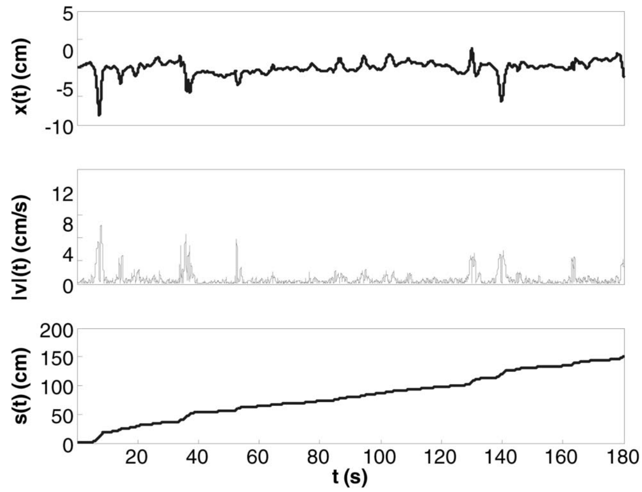

Figure A2. Plot of a typical mean-centered and filtered time series taken from the sacral marker (upper), its absolute velocity (middle), and the cumulative distance traveled (lower), all plotted as functions of time.

To assess the total amount of movement for the head, waist, and hand, each respective signal was differenced to acquire the approximate velocity profile, such that

$$v_i = x_i - x_{i-1}, \tag{A2}$$

where v is velocity, x is position and i is the sample index. The absolute values of the resultant output vector were summed with respect to time to achieve total one-dimensional displacement,

$$d = \sum_{i=2}^{N} |v_i|, \tag{A3}$$

where d is displacement, v is velocity, i is the sample index, and n is the total number of samples. An example of a time series and its velocity profile can be seen in Figure A2.

(*Appendices continue*)

Gaze Data

Noise in gaze data may exist because of the participant blinking or the eye-tracker losing focus on the relevant portion of the eye. Although there are many ways to preprocess gaze data (Salvucci & Goldberg, 2000), for this analysis the simplest methods were used. First, any data that fell outside the area of calibration were discarded. Second, data in the *x* and *y* planes were converted to velocity profiles, and any points which exceeded expected peak saccade velocity of 600°/s (visual angle) were removed (Duchowski, 2007). Finally, a nearest-neighbor interpolation algorithm filled in the missing data points. The preprocessing resulted in 20 trials with greater than 10% missing gaze data, which were discarded from analysis. Further, one pair had greater than 10% missing eye data in 8 out of the 9 trials, which resulted in 17 usable pairs for gaze analysis.

Appendix B

Cross-Recurrence Quantification of Movement Data

Before conducting CRQ, the phase space for the two time series to be compared must be reconstructed. Phase space reconstruction (Abarbanel, 1996) exploits the fact that variables in nonlinear systems interact and mutually constrain one another. Because of this pervasive interdependence, one can use a single observable scalar time series to reconstruct the higher dimensional domain in which the system under consideration exists. This is accomplished by using time-delayed copies of that signal as surrogates for the other variables governing the system. With an appropriate time delay, the surrogate dimensions of the reconstructed phase space are independent enough to generate new information, but not so independent as to be essentially unrelated. Selecting the length of this delay is the first step in phase space reconstruction. One recommended heuristic, and the method used here, is to compute the average mutual information (AMI; a measure of the correlated activity between signals) of the time series across a span of delays, and then choose the first local minimum of the resultant function. An example of such a plot can be seen in Figure B1.

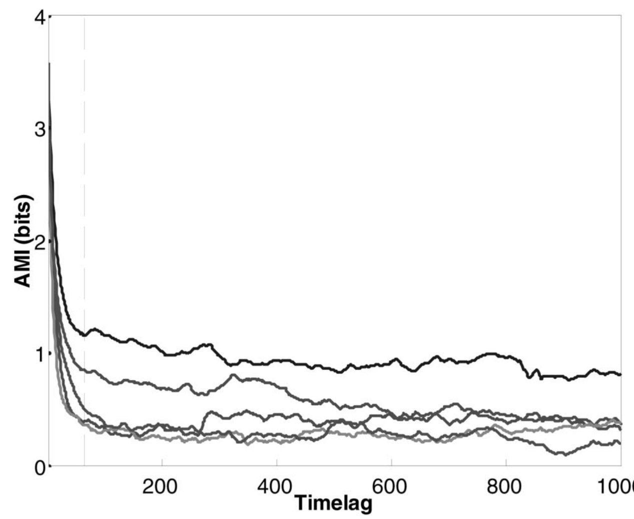

Figure B1. Average mutual information (AMI) calculated for five randomly chosen time series recording head movement in the AP direction. The dashed line corresponds to the mean first minimum of average mutual information calculated for all pairs, in this case a delay of 63 samples (sampling rate set at 30 Hz). Similar patterns were observed for the measurements taken at the waist and at the hand.

Once an appropriate time delay is chosen, the next step is to choose the number of dimensions in which to embed the original time series. Evaluating a system in a lower dimensional space than that would sufficiently capture the degrees of freedom of the system in question can result in false neighbors, where points in the phase space which are not actually near to one another appear as neighbors in the reconstructed space. A suitable embedding dimension can be estimated using a false-nearest neighbors (FNN) analysis, which detects how many points that are neighbors in a lower dimension stay neighbors in a higher dimension, and conversely, the number that do not. The process of calculating FNN begins with an embedding dimension of one, and then iteratively calculates FNN for each subsequently higher embedding dimension until that number drops to zero (or to its minimum). Plots of FNN for each signal can be seen in Figure B2.

CRQ is the application of a Heaviside function to a distance map. In other words, once the signals are unfolded in the higher dimensional phase space, the Euclidean distance between all points are calculated, and those points that fall within some predefined radius are considered recurrent. Therefore, once the appropriate delay and number of dimensions has been chosen, the final step is to choose the appropriate radius according to several guidelines. First, it is important that the chosen radius falls within the linear region of a double logarithmic plot of radius and %REC (Webber, 2005). If the radius is too low, then there may be oscillations in the values of %REC within narrow bands of given radii, which are possible indications of noise in the signal (Riley, Balasubramaniam, & Turvey, 1999). Second, it is important to select a radius such that the cross-recurrence map is sparse, so that the analysis focuses on local points. Third, it is recommended to plot %REC for a variety of parameters, and chose from the range in which

(*Appendices continue*)

%REC changes smoothly, as rapid fluctuations may mean that there is a change in the scale of the behavior of the system, which could unduly affect CRQ variables (Shockley, 2005). Following these guidelines, a radius of 27% of the mean rescaled distance of the phase space was chosen for each body segment time series. To check that an appropriate set of parameters has been chosen, it is generally recommended to compare CRQ output of a regular signal to that of a randomly shuffled signal (see Figure B3). Because the random shuffling destroys the temporal order of the measurement, the values of obtained CRQ variables are expected to drop considerably, and this drop was observed in the present data set.

Cross Recurrence Quantification of Gaze Data

CRQ of gaze data was similar to CRQ of movement data in terms of how the measures were calculated. However, the phase space reconstruction procedure described above was not used. Rather, the *x* and *y* coordinates were embedded in a two-dimensional map, with no time delay. A radius of 2.54 cm was used to determine the recurrence neighborhood. Additionally, a window of 3,000 ms was used to restrict the outcome measures of the recurrence plots to locally recurrent points (Richardson et al., 2007).

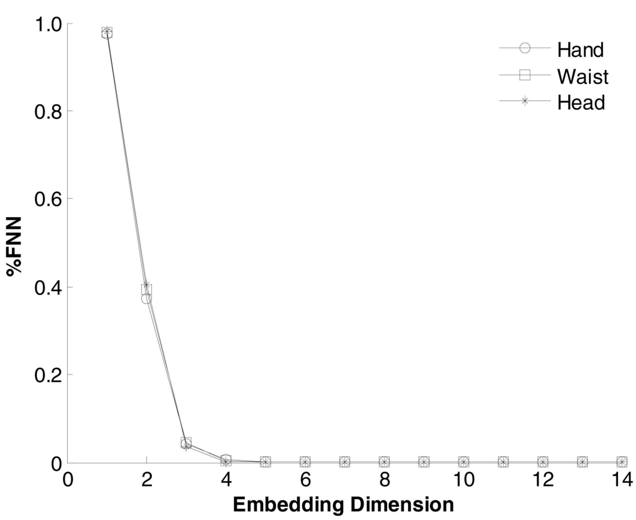

Figure B2. Average percentage of false nearest neighbors (FNN) across all trials for all pairs as a function of embedding dimension (time delays of 59, 63, and 57 were used for the hand, waist, and head, respectively). It can be seen that FNN drops to zero at an embedding dimension of five for all three locations. To make sure that all evaluated time series were fully unfolded, an embedding dimension of seven was used for all three sensor locations.

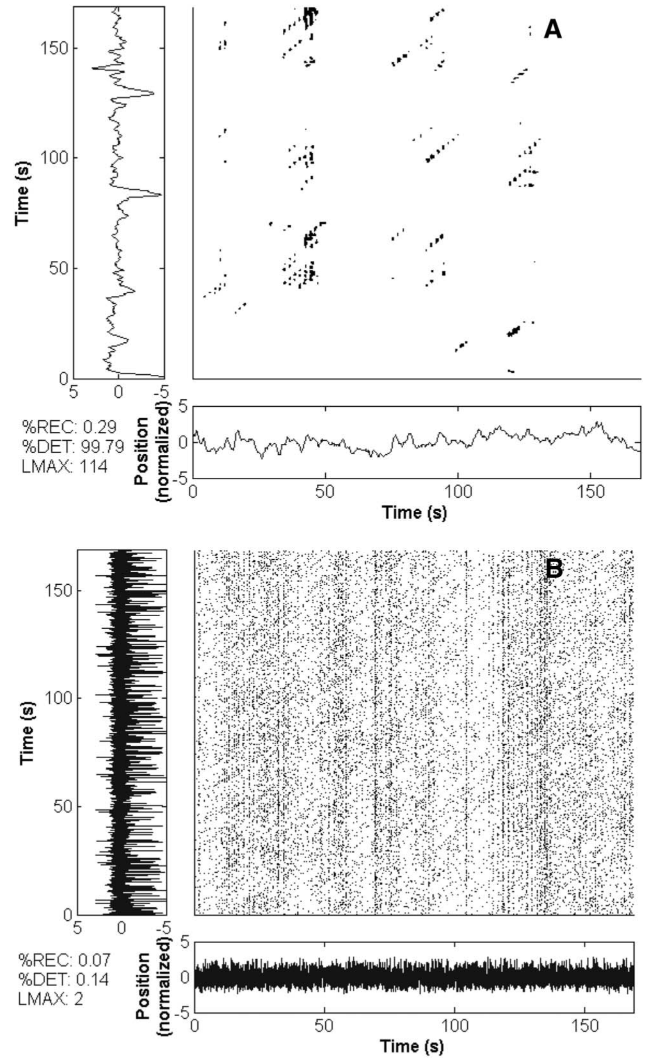

Figure B3. CRQ plots created using waist data from a pair in the RR condition. (A) Normal time series. (B) Randomly shuffled time series from the sample shown in Panel A.

Received October 24, 2013
Revision received May 30, 2014
Accepted June 2, 2014 ■