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I, Michael T. Tolston , hereby submit this original work as part of the requirements for the degree of Master of Arts in Psychology.

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Movement constraints on interpersonal coordination and communication

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Abstract

The present study investigated whether constraining movement affects interpersonal coordination and cognitive performance. Participants worked in pairs to complete a series of cooperative picture-puzzle tasks in which they discussed and found differences between their respective puzzles relying only on verbal communication. Pairs participated in each of three degree-of-constraint conditions: either both participants were free to move their hands (FF), both participants had their hands restrained (RR), or one participant (Person 1) had his or her hands restrained while the other was free to move (FR). During any given trial, neither participant was informed of the degree-of-constraint of his/her partner. Eye tracking data was collected, and movement was measured at the waist, hand, and head in the Anterior-Posterior (AP) direction. Data were analyzed using Cross-Recurrence Quantification Analysis (CRQ) and Joint-Recurrence Quantification Analysis (JRQ). Postural sway coordination, gaze coordination, as well as cognitive performance were predicted to be highest in FF, followed by RR. The lowest degree of coordination and cognitive performance was expected to be found in the FR condition.

Results showed that whenever there were significant differences in coordination patterns between conditions, the asymmetric condition generally exhibited lesser degrees of coordination, and that, whenever there was a difference in the overall amount of coordination, the condition in which both participants were free to move exhibited greater coordination. However, it was also the case that the structural patterning of coordination was dependent upon the location of measurement for the conditions in which both individuals were restrained and when both individuals. Additionally, in spite of the fact that the restraint manipulation did not have a significant influence on task performance, correlations between task performance and movement measures showed significant positive relationships between movement, number of

utterances, and number of differences found, indicating a relationship between movement and task performance consistent with my hypotheses. Taken in sum, these results show that both coordination and cognitive performance are sensitive to constraints placed the action system.

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CHAPTER 1

Introduction

From simple exchanges between polite strangers on the street, to drinks with friends, to bartering down the price of a gold necklace in an Arabian souq, conversation cuts a wide swath across all of our daily lives. While a ubiquitous social occurrence, the complexity underlying communication has caused it to appear rather opaque to scientific inquiry, and conventional research methods and data analyses are not well equipped to handle the richness of the phenomenon. However, recent advances in theory and methodology, such as the conceptual frameworks of embodiment, situated psychology, and dynamical systems, along with non-linear methods of quantifying complex data, have opened up new avenues of exploration. Motivated by these advances, I designed the present research to further investigate the relationship between movement, interpersonal coordination, and communication.

Embodiment

Recent investigations which have explored the interrelation between body states and cognition are generally referred to as embodied approaches (Clark, 1999; Shapiro, 2011). These frameworks assume that the processes governing cognition and behavior are not solely a function of the brain, but emerge as an interaction between cognitive and motor domains. For example, individuals who are allowed to freely move their hands exhibit better performance on a memory task than those whose gestures are restricted (Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001). In their experiment, Goldin-Meadow et al. asked participants to solve a math problem, and then commit a series of letter strings to memory. Participants were then asked to explain how they solved the math problem in one of two conditions: either they were free to move their hands, or their movements were restricted. Participants who were allowed to gesture

freely were able to recall more letter strings than those who were not able to move their hands. The authors suggest that gesturing may distribute the cognitive burden across the resources available to the system and thereby increase task performance.

A similar study by Morsella and Krauss (2004) has also extended our understanding of the relationship between manual gesturing and the co-extensive process of articulation. In this study, individuals were tasked with describing a series of pictures, some of which were simple drawings of everyday objects (e.g., a clock, a flower), while others were abstract squiggles with no common name or purpose. To test the relationship between gesturing and working memory, individuals were either tasked with describing the pictures from memory, after having seen them for a period of time, or they were asked to describe them while the pictures were still present. To evaluate the role which gesturing has in speech production, individuals were either allowed to move their hands or had their hands restrained through a deception. Results showed that individuals gestured more in the stimulus-absent conditions than in the stimulus-present conditions, more evidence which supports the proposition that gesturing facilitates recall. There was also more gesturing in the conditions where participants described meaningless stimuli versus pictures of familiar, everyday items, which indicates that gesturing also aids performance in difficult lexical tasks. Finally, it was shown that restraining hand motion significantly lowered the speech production rate of participants, again illustrating a bi-directional causal link between processes which are traditionally relegated to the cognitive domain and motor behavior.

Additional evidence for the embodiment of cognition is illustrated by Glenberg and Kaschak's (2002) study, which showed that when actions are compatible with semantic content of stimuli, reaction time is reduced. For example, when responding whether or not a given

statement makes sense (e.g. close the door versus close the plate), participants are quicker to react if the button placement associated with the correct answer corresponds to the direction in which the action would take place spatially, supporting the interpretation that language comprehension is grounded in the action system.

Additional studies linking the motor system with cognitive processes have used computer mice to continuously track hand movement while participants perform decision tasks. For example, participants asked to click on a picture of a stimulus corresponding to a given name took a longer time to reach the appropriate response if there was a distractor picture which shared phonological similarities with the target picture (e.g., candle and candy versus candle and jacket) (Spivey, Grosjean, & Knoblich, 2005). Further, the trajectories of hand motion were longer in the latter conditions than in the former. Another study used the same method to investigate the impact of ambiguity in the veracity of statements worded as questions (e.g., “Should you brush your teeth every day?”, which is not ambiguous, versus “Is murder sometimes justified?” , a question that has no clearly defined answer) (McKinstry, Dale, & Spivey, 2008). Similar to the previous study, participants moved more slowly and their movement trajectories were longer when answering questions which were ambiguous compared to straightforward. These two studies show that the underlying dynamics of cognitive processes can be revealed through careful analysis of motor behavior.

Taken together, these studies implicate the motor system in a wide range of cognitive processes that have historically been investigated without reference to motor activity. Including the motor system in the explanatory framework of these processes offers to lend insight into the constraints and underlying dynamics that govern cognition.

Interpersonal Coordination

Body and Speech. It is well established that individuals exhibit coordination in speech patterns and body movement, both with themselves and with others. For example, investigations of speech patterns of interviewers and interviewees, Street (1984) demonstrated that both parties converged in overall speaking rate and in the time they took between responses. Natale (1975) also showed this coordination in less structured scenarios, where dyads engaged in free dialogue showed a convergence of speech patterns in terms of pausing and turn taking. In another classic study, intra-personal movements were shown to correlate with articulation, meaning that individuals tend to synchronize their body with their speech (Condon & Ogston, 1967). The same study investigated interpersonal coordination observed in the videotaped interaction of a mother, father and son, and found what the authors reported to be a surprising amount of nearly instantaneous synchrony between all three subjects, with all observed movements within individuals having some type of effect on the movements of the other two. More recently, it has also been demonstrated that individuals spontaneously coordinate postural sway during conversation (Shockley, Santana, & Fowler, 2003). In their experiment, Shockley et al. measured postural sway of participants solving a puzzle task in which they were instructed to work together to enumerate differences in pairs of nearly identical pictures. The experimenters manipulated the direction the participants were facing, as well as whether the participants worked on the task together or separately with confederates. They found a greater degree of coordination between individuals when they were working together versus when they were working with confederates, and, somewhat surprisingly, this effect was not moderated by whether or not participants had visual access to one another. In other words,

simply engaging in a conversation with each other was sufficient to enhance the similarity of participants' movements.

Indeed, this tendency toward synchrony between conspecifics is a general phenomenon that arises in a variety of contexts. For example, individuals have been shown to spontaneously coordinate limb segments while swinging pendulums (Schmidt & O'Brien, 1997) and to oscillate in synchrony while seated in rocking chairs (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007). In the former study, participants were instructed to each swing a pendulum at a comfortable self-chosen tempo while seated next to each other. It was expected that there would be only chance level coordination during this movement, and that was, in fact, observed. In the second part of the experiment, participants were instructed to swing their pendulums at the same tempo as before, but this time while looking at the person next to them. In this condition, participants spontaneously coordinated their pendulum swinging, and showed a distinct bias towards coordination modes corresponding to dynamically organized processes of coordination demonstrated previously within (Haken, Kelso, & Bunz, 1985) and between individuals with instructions to coordinate (Schmidt, Carello, & Turvey, 1990). Critically, the stable modes of coordination pulled individuals into a relatively synchronous state, even though they were instructed to perform the task independently, and were shown in earlier trials to be able to do so. Participants apparently could not help but coordinate their movements when they saw the other person. Using similar methodology, M.J. Richardson et al. (2007) demonstrated these same principles of organization are also at work in more general settings. Namely, to help verify that the spontaneous coordination exhibited by participants swinging pendulums is not an artifact induced by the highly structured nature of the task, the researchers investigated rhythmic coordination in a more ecological setting. Participants seated in adjacent rocking

chairs were instructed to rock at their own preferred tempo, and the researchers manipulated their visual access to one another, as well as the natural frequencies of the rocking chairs (i.e. by placing a variable amount of weight under the seat of the chairs). The researchers demonstrated that individuals spontaneously coordinated their rocking tempos when they focused their visual attention in the region of their partner, and this coordination occurred even if their rocking chairs had different natural rocking frequencies. These results provide evidence that the findings revealing spontaneous interpersonal coordination of limb segments during rhythmic tasks generalize to whole body coordination patterns, and that this coordination is at least somewhat robust against detuning.

Gaze. In recent years, studies in interpersonal coordination have begun to look at gaze coordination and what it can tell us about communication and understanding. In one study, researchers recorded monologues of individuals discussing the characters on a popular television show (D.C. Richardson & Dale, 2005). This was done while the participants were looking at screen with a matrix of pictures of the characters, while researchers recorded their gaze trajectories with eye tracking technology. Later, other participants listened to the monologues while their gaze trajectories were tracked. The researchers found that the gaze patterns of the speaker and the listener were significantly coordinated within a 3s window, with a peak overlap of gaze occurring at 2s. 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 monologue, demonstrating an important link between gaze coordination and comprehension.

A similar study examined the coordination that emerges between participants engaged in dialogue, rather than listening to or producing monologues (D.C. Richardson, Dale, & Kirkham,

2007). Prior to engaging in an extemporaneous discussion a famous work of art, participants heard a short monologue, either regarding the biography of the painter or of particular aspects of his style of painting. The particular pairings of monologues which were played to the participants were different between dyads, with some participants hearing the same background information, while others heard different monologues. Interestingly, when individuals listened to the same background information, their gaze patterns were more coordinated than otherwise, indicating that measurements of gaze coordination are sensitive to factors as subtle as individuals being exposed to dissimilar background information. Additional research has demonstrated that participants' beliefs play an important role in gaze coordination. Specifically, researchers manipulated individual's beliefs regarding whether or not a partner has access to a visual scene pertinent to their ongoing conversation (D.C. Richardson, Dale, & Tomlinson, 2009). Participants who were discussing a previously viewed video clip coordinated their gaze patterns more tightly if they thought their partner did not have access to a visual cue, further evidence that measurable body states are strongly related to complex cognitive processes, and that the sensitivity of these processes to the states of another person is extremely important. Examining and understanding these interactions is likely to play an important role in understanding the nature interpersonal coordination in effective communication.

Embodied Communication?

Given that body states have been shown to be meaningfully and causally connected to mental states, and vice versa, and that individuals spontaneously coordinate body movements as well as speech and gaze patterns during conversation, it is likely that restraining movement should interfere with both interpersonal coordination as well as communication between co-present interlocutors. Thus, the present research was designed to investigate the relationship

between movement 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. Shockley et al., 2003) in one of three degree-of-constraint conditions: either both participants were *free* to move their hands (FF), both participants had their hands *restrained* (RR), or one participant was *free* to move while the other had his or her hands *restrained* (FR). During a given trial, neither participant was aware of the degree-of-constraint of his or her partner. I predicted that postural coordination, gaze coordination, and cognitive performance would all be highest in the condition in which both participants were free, followed by the condition in which both participants were restrained. I expected the lowest degree of coordination and cognitive performance in the condition in which one participant was restrained while the other was not. This prediction was based on the asymmetry involved in the manipulation and the sensitivity of postural sway trajectories to supra-postural tasks (Bardy, Hettinger, Pagulayan, Stoffregen, 2000; Gardner Lavie, Leadbetter, & Yardley 1999). Specifically, it has been demonstrated that voluntary arm movements affect postural stability (Patla, Ishac, & Winter, 2002), thus conditions in which one participant was free to move while the other was restrained would likely result in qualitatively different patterns of postural sway, which should negatively affect the degree of coordination that I observed between individuals.

CHAPTER 2

Method

Participants

Forty participants (20 pairs) took part in this experiment: 18 were recruited from the University of Cincinnati Psychology Participation Pool, and 2 were recruited from fliers advertising a cash incentive of \$5/.5 hr. Two pairs failed to complete the task, and their data were discarded. All participants were screened for the absence of neurological and movement disorders, balance problems, motion sickness, allergies to latex and spandex, and for the presence of normal or corrected to normal vision. Participants were also screened for any recent injuries that impair their ability to move or stand. Only individuals who spoke English as a primary language were recruited to participate.

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 was collected at 60 Hz, but down sampled to correspond to the collection frequency of waist and hand data). Eye tracking data was collected at 60 Hz using a head-mounted near infra-red eye-tracking system (EYE-TRAC 6 Head Mounted, Applied Science Laboratories, Bedford, MA). Nineteen pairs of full-color cartoon pictures printed on 61 × 69 cm poster board were used as stimuli. All stimuli were presented one at a time at approximately eye height level and at a distance of 1.8 m from the participants.

Procedure

The University of Cincinnati Institutional Review Board approved all experimental protocols. A written informed consent was administered to all participants prior to starting any experimental trial, to which all participants agreed. After all trials were completed, a survey was administered to be used for subsequent data mining on other social factors that may influence coordination, but were not part of the present study.

Following a briefing of 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 with their feet at shoulder width, and were assisted in donning the eye-tracking headgear, to which a motion tracking sensor was rigidly affixed. An elastic strap with an attached motion capture sensor was placed around the waist of each participant to track postural sway (cf. Shockley et al., 2003). The participants donned a tie-on waist apron with two large pockets in the front, to allow a means for restraining hand motion. A short calibration was then conducted to adjust the eye tracking equipment to each participant. After a successful calibration, an opaque curtain was drawn down the center of the chamber to visually isolate the participants from each another. Prior to each trial, participants were informed of their degree-of-restraint 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 stimuli. For those trials in which the participant was to be restrained, the sign read “In this trial you are restrained. Please place your hands your pockets”, while 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 prior to beginning each trial. In all conditions, participants worked together to solve a picture-puzzle task, in which each participant viewed one picture out of a complimentary pair of pictures. The paired pictures were identical, with the exception of 10 slight differences, and participants were tasked to find and enumerate the differences between their two pictures by describing their pictures to one another. While the participants were solving the puzzles, the researchers kept track of the number of differences they found in order to index task performance.

Design

Degree-of-restraint was manipulated as a within-subjects variable by placing upper extremity movement restrictions on person 1 and on person 2 (RR), neither on person 1 nor on person 2 (FF), or on person 2 alone (FR). Conditions were blocked together and randomized between pairs, with each condition having three trials, as well as a single practice trial in which both participants were free to move their hands. This resulted in 10 total trials per dyad, with each trial lasting 3 minutes. The effects of restraining hand motion were assessed with respect to total movement, interpersonal coordination, and task performance. For each measure, the resultant variables were averaged across three trials for each condition for each participant pair, yielding a single observation for each pair in each condition. Due to time constraints that resulted from hardware complications, pair 1 only performed 2 trials in the FR condition, while pair 11 only performed 2 trials in each condition.

Prior to submission to analysis, the Grubb's outlier test was used to assess the raw data for outliers within each condition at the individual trial level, and again after the averages were

calculated (see Table 2.1). 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, then they were removed from that analysis. In pair 15, the waist data for Person 2 was excessively noisy, possibly due to 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; see below for descriptions of these measures) were submitted to one-way repeated measures analyses of variance (ANOVAs), while total movement and total utterances were submitted to 2-way mixed AVOVAs with restraint as the within-subjects factor and person as the between-subjects factor. Pearson correlations were also calculated between task performance and behavioral measures.

Table 2.1

Number of outliers removed from analysis, broken down by trial, average, and location.

Location	Condition	Trial			Average		
		%REC	%DET	LMAX	%REC	%DET	LMAX
Hand	FF	0	1	0	0	0	0
	FR	3	4	2	0	2	0
	RR	5	3	2	0	0	0
Waist	FF	2	1	0	1	0	0
	FR	1	2	2	0	0	0
	RR	2	0	1	0	0	0
Head	FF	2	1	2	0	0	1
	FR	2	0	4	0	0	0
	RR	8	0	7	0	0	1
Gaze	FF	1	0	0	0	0	0
	FR	3	0	2	1	0	1
	RR	2	0	1	0	0	0
JR Hand-Gaze	FF	0	2	1	0	0	1
	FR	2	0	1	0	0	0
	RR	6	0	0	1	0	0
JR Waist-Gaze	FF	2	1	1	0	0	1 ^a
	FR	4	0	2	0	0	2 ^a
	RR	5	1	1	0	0	0
JR Head-Gaze	FF	3	0	1	0	0	0
	FR	2	2	0	0	0	0
	RR	3	0	1	0	0	1

Note. JR: Joint Recurrence.^aPair 13 was an outlier in JRQ Waist-Gaze for FF and FR in LMAX, and was thus removed from that analysis

Data Processing and Reduction

Movement Data. All reported movement data are along the anterior-posterior (AP) axis. Prior to analysis, movement signals from the waist, hand and head were filtered using a 2nd order high pass Butterworth filter. Selection of a filtering parameter was achieved through residual analysis (Winter, 2005), which was completed 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

$$R(f_c) = \sqrt{\frac{1}{N} \sum_{i=1}^N (X_i - \hat{X}_i)^2}, \quad (1)$$

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 . Since the filtering 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 2.1), 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 analysis was the average of these values, resulting in a chosen filtering frequency of 2.67 Hz for the waist ($SD = .51$), 3.03 Hz for the hand ($SD = 1.11$), and 3.66 Hz for the head ($SD = .55$).

In order to assess the total amount of movement for the head, waist, and hand, each respective signal was differentiated in order to determine the velocity profile, such that

$$v = \frac{dx}{dt}, \quad (2)$$

where v is velocity, x is position and t is time. The absolute values of resultant output vector were summed with respect to time to achieve total distance traveled,

$$d = \int |v| dt, \quad (3)$$

where d is distance, v is velocity, and t is time. An example of a time series and its velocity profile can be seen in Figure 2.2.

Gaze Data. Noise in gaze data may exist due to the participant blinking or the eye-tracker losing focus on the relevant portion of the eye. While there many ways to pre-process gaze data (Salvucci & Goldberg, 2000), for this analysis the simplest methods were employed. First, any data which 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 °/sec (visual angle) were removed (Duchowski, 2007). Finally, a nearest-neighbor interpolation algorithm filled in the missing data points. The pre-processing 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.

Figure 2.1. Residual analysis for a range of cut-off frequencies (f_c). 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-square-fit line for the waist and random data (noise) plotted as solid lines. The variable location at which the residuals equal the intercept demonstrates different movement frequencies of the various body segments. It is interesting to note that, while the residuals from the head marker approach their respective asymptote faster, the recommended filtering frequency for the waist is lower. This is due to the different amount of noise in the two signals, with the estimated amount of noise in the waist signal being .042 cm (RMS) while the estimated noise of the hand sensor is a mere .002 cm (RMS), likely due to the motion tracking equipment being closer to the head than to the waist. 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 2.2. Plot of a typical mean-centered and filtered time series taken from the sacral marker (upper), its absolute velocity (middle), and cumulative distance travelled (lower) all plotted as functions of time

Cross Recurrence Quantification of Movement Data. Following data reduction, the postural sway time series and gaze-trajectory time series were submitted to *Cross Recurrence Quantification (CRQ) Analysis*, a nonlinear analysis method which allows one to compare how two time series evolve similarly over time (e.g., Shockley et al., 2003; D. C. Richardson et al., 2005). 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 which does not require that the data adhere to the assumptions required by linear methods. CRQ measures %REC, the number of shared data configurations relative to all possible configurations (a nonlinear measure similar to linear cross correlation), %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 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) were used to measure the magnitude and stability of both movement and gaze coordination between members of a conversational pair.

Prior to 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 non-linear 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 randomly related (Abarbanel, 1996), and selecting the length of this delay is the first step in phase space reconstruction. One recommended heuristic, and the method used in this analysis, 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 minimum of the resultant graph. An example of such a plot can be seen in Figure 2.3.

Figure 2.3. Average mutual information (AMI) calculated for ten 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 which 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 2.4.

Figure 2.4. 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 5. To make sure that all evaluated time series were fully unfolded, an embedding dimension of 7 was used for all three sensor locations.

CRQ is, in the simplest terms, 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 which fall within some pre-defined 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, and 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 in the range in which the variable 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 sensor. 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 2.5). Since 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.

Figure 2.5. 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.

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 2-dimensional map, with no time delay. A radius of 1 in. was used to determine the recurrence neighborhood. Additionally, a window of 3000 m/sec. was used to restrict the outcome measures of the recurrence plots to locally recurrent points (D.C. Richardson, et al., 2007).

Joint Recurrence Analysis. While CRQ is a useful tool for studying dynamical systems, it is limited to cases in which the systems under consideration share common phase space parameters. If one wants to investigate the relationship between qualitatively different types of systems (e.g., similarity of coordination of body segments with coordination of gaze trajectories), one possible strategy is to use of Joint Recurrence Quantification Analysis (JRQ) (Marwan, Romano, Thiel, & Kurths, 2007). Essentially, JRQ evaluates the probability of finding recurrent points of two systems in their individual state spaces occurring at the same time, giving a measure of the coupling between the two systems. Typically, this is accomplished using auto-recurrence to evaluate two signals independently, and then using the resultant recurrence plots to index the points in time which they are simultaneously recurrent. However, for the current analysis, cross-recurrence plots were used with this method, giving an index of the higher-order coordination dynamics that exist between the various segments of two individuals engaged in conversation (i.e., coordination of heads concurrent with coordination of gaze; coordination of waists concurrent with coordination of eyes).

CHAPTER 3

Results

Only those analyses with statistically significant results are reported.

Movement

Mean results for the effect of restraint on %REC, %DET and LMAX at the hand are shown in Figure 3.1. Analysis showed a main effect of restraint on total movement, $F(2,68) = 29.70, p < .001, \eta_p^2 = .466$. There was no effect of person on degree of movement at the hand, $F(1,34) = 2.02, p = .165, \eta_p^2 = .056$, but there was a significant interaction between restraint and person, $F(2,68) = 8.59, p < .001, \eta_p^2 = .202$. Simple main effects showed a significant difference between amounts of hand movement at the level of FR, with person 1 moving more than person 2, $p = .01$, indicating that the manipulation was as intended, with the degree of hand movement being substantially different between persons in the asymmetric condition, but not in the other two conditions.

Figure 3.1. Mean values total movement at the hand. Error bars represent one standard error.

Movement Coordination

Hand. The mean results for the effect of restraint on %REC, %DET and LMAX at the hand are shown in Figure 3.2. Restraint had a significant effect on %REC, $F(2,34) = 11.78$, $p < .001$, $\eta_p^2 = .409$, on %DET, $F(2,34) = 7.73$, $p = .002$, $\eta_p^2 = .313$, and on LMAX, $F(2,34) = 4.59$, $p = .017$, $\eta_p^2 = .206$. Planned comparisons revealed that %REC was significantly higher in FF than in FR ($p = .001$) or RR ($p = .002$), meaning that individuals exhibited a greater amount of shared configurations when they could both move their hands compared to when one person was restrained. Further planned post hoc analyses showed that %DET was significantly higher in RR than in FF ($p = .02$), while LMAX was significantly higher in FF than in FR ($p = .016$). These last two results suggest that the overall structure was more deterministic when both individuals were restrained compared to when they were both free to move, and that the overall the coordination pattern was more stable when individuals could both move their hands compared to when one person was restrained.

Figure 3.2. Mean values from CRQ analysis of hand data. Error bars represent one standard error.

Waist. The mean results for the effect of restraint on %REC, %DET and LMAX at the waist are shown in Figure 3.3. Mauchly's test of sphericity was significant for LMAX, $p = .005$,

thus results were corrected with the Greenhouse-Geisser method. Restraint had a significant effect on %DET, $F(2,32) = 3.44$, $p = .044$, $\eta_p^2 = .177$, as well as on LMAX, $F(2,32) = 5.18$, $p = .025$, $\eta_p^2 = .245$. A planned comparison showed that %DET was significantly higher in RR than in FR, $p = .035$, meaning that the coordination was more deterministic when both individuals were restrained compared to when one was free and the other was restrained, while a Bonferroni corrected post hoc analysis revealed that LMAX was significantly higher in RR than in FR, $p = .007$, meaning that overall stability of coordination was higher when both individuals were restrained compared to when one individual's hands were free to move.

Figure 3.3. Mean values from CRQ analysis of waist data. Error bars represent one standard error.

Head. The mean results for the effect of restraint on %REC, %DET and LMAX at the head are shown in Figure 3.4. Mauchly's test of sphericity was significant for %REC, $p = .012$, and also for LMAX, $p = .001$, therefore results for those measures were corrected with the Greenhouse-Geisser method. Analyses revealed a significant effect of restraint on %REC, $F(2,34) = 7.41$, $p = .002$, $\eta_p^2 = .304$, and also on LMAX, $F(2,34) = 13.62$, $p < .001$. Bonferroni corrected post hoc analyses showed that %REC was significantly higher in FF than in FR, $p = .009$, meaning that there was a greater amount of overall coordination of the head between individuals when they could both move their hands compared to when one person was

restrained. Further Bonferroni corrected post hoc analyses showed that LMAX was significantly higher in FF than in either FR ($p = .004$) or RR ($p = .004$), meaning that coordination patterns of movement of the head were more stable when both individuals could move compared to when they were both restrained or when one person was restrained and the other was free to move.

Figure 3.4. Mean values from CRQ analysis of head data. Error bars represent one standard error.

Gaze. The mean results for the effect of restraint on %REC, %DET, and LMAX are shown in Figure 3.5. Mauchly's test of sphericity was significant for %REC, $p = .026$, thus results for that measure were corrected with the Greenhouse-Geisser method. Analysis of gaze overlap showed a significant main effect of restraint on %REC, $F(2,32) = 4.89$, $p = .026$, $\eta_p^2 = .234$, however, Bonferroni corrected post hoc analyses showed no difference between conditions. Restraint also affected gaze %DET, $F(2,32) = 3.81$, $p = .033$. Planned comparisons showed a significantly higher %DET in the FF than in the FR condition ($p = .025$), meaning that the pattern of gaze coordination was more structured when both individuals were free to move their hands compared to 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 to FR ($p = .011$), and also higher in RR

compared to FR ($p = .015$), indicating that when 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 to when one person's hands were restrained while the other person was free to move.

Figure 3.5. Mean values from CRQ analysis of gaze data. Error bars represent one standard error.

Joint Recurrence Quantification Analysis

Hand. The mean results for the effect of restraint on %REC, %DET and LMAX on the joint recurrence between hand and gaze are shown in Figure 3.6. Restraint had a significant effect on %REC, $F(2,32) = 8.02$, $p = .002$, $\eta_p^2 = .334$, with planned comparisons revealing that %REC was significantly higher in FF than in FR ($p = .034$) or RR ($p = .003$). This means that hand and gaze were coordinated at the same time more frequently in FF than in either FR or RR.

Figure 3.6. Mean values from JRQ analysis of hand and gaze data. Error bars represent one standard error.

Waist. The mean results for the effect of restraint on %REC, %DET and LMAX on the joint recurrence between waist and gaze are shown in Figure 3.7. Restraint had a significant effect on %REC, $F(2,30) = 7.03, p = .003, \eta_p^2 = .319$, %DET, $F(2,30) = 4.27, p = .023, \eta_p^2 = .222$, and also on LMAX, $F(2,28) = 7.67, p = .002, \eta_p^2 = .353$. Planned comparisons revealed that %REC was significantly higher in FF than in FR ($p = .008$), and was also higher in RR than in FR ($p = .007$). This means that hand and gaze were coordinated between participants at the same time more frequently in FF and RR than in FR. Planned comparisons of %DET showed significant differences between FF and FR ($p = .027$), meaning that the structure of simultaneous coordination of waist and gaze was greater when both participants could move their hands versus when one participant was restrained. Pairwise comparisons also showed that LMAX was longer in FF than FR ($p = .002$), and also that LMAX was longer in RR compared to FR ($p = .003$), meaning that the overall stability of simultaneous coordination between waist and gaze was higher in FF and RR than in FR.

Figure 3.7. Mean values from JRQ analysis of waist and gaze data. Error bars represent one standard error.

Task Performance.

The mean results of the effects of restraint on task performance can be seen in Table 3.1.

Correlations between task performance and other behavioral measures can be seen in Table 3.2.

Table 3.1

Task Performance by Condition

Measure of Task Performance	<i>M</i>			<i>SD</i>		
	FF	FR	RR	FF	FR	RR
Differences Found	5.64	5.88	6.00	0.93	1.14	0.98
Utterances Person 1	285.07	279.22	285.31	75.17	81.99	66.18
Utterances Person 2	252.20	260.83	251.30	77.25	76.52	71.45
Utterances of Pair	266.74	268.69	266.34	77.39	78.89	70.55

Table 3.2

Correlations of Task Performance Variables with Behavioral Measures

	A			B			AB			Diff		
	<i>r</i>	<i>p</i>	<i>N</i>	<i>r</i>	<i>p</i>	<i>N</i>	<i>r</i>	<i>p</i>	<i>N</i>	<i>r</i>	<i>p</i>	<i>N</i>
A				-0.34	0.01	54	0.57	0.00	54	0.29	0.03	54
B	-0.34	0.01	54				0.58	0.00	54	*	*	*
AB	0.57	0.00	54	0.58	0.00	54				0.28	0.04	54
%DET Hand	*	*	*	*	*	*	-0.38	0.01	52	*	*	*
%DET JWG	-0.36	0.01	49	*	*	*	*	*	*	*	*	*
DIFF	0.29	0.03	54	*	*	*	0.28	0.04	54	*	*	*
DMAX Gaze	-0.33	0.02	50	*	*	*	*	*	*	*	*	*
DMEAN Gaze	-0.35	0.01	50	*	*	*	*	*	*	*	*	*
DMEAN Head	*	*	*	*	*	*	-0.27	0.04	54	*	*	*
Hand P1	0.27	0.05	54	0.29	0.03	54	0.49	0.00	54	0.32	0.02	54
Head P1	0.27	0.05	54	*	*	*	0.45	0.00	54	0.40	0.00	54
Head P2	*	*	*	0.41	0.00	54	*	*	*	*	*	*
LMAX Hand	-0.29	0.04	54	*	*	*	*	*	*	*	*	*
%REC JHG	*	*	*	0.28	0.04	51	*	*	*	*	*	*
Waist P1	*	*	*	*	*	*	*	*	*	0.36	0.01	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; JHG: JRQ Head-Gaze; 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.

CHAPTER 4

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, followed by when both participants were restrained, and that both would be lowest when one participant was restrained and the other was free to move. The results partially support these hypotheses, in that whenever there were significant differences in coordination patterns between conditions the asymmetric condition generally exhibited lesser degrees of coordination, and that, whenever there was a difference in the overall amount of coordination, the condition in which both participants were free to move exhibited greater coordination. However, it was also the case that the conditions in which both individuals were restrained and when both individuals were free showed structural patterning of coordination which was dependent upon the location of measurement. Additionally, in spite of the fact that the restraint manipulation did not have a significant influence on task performance, correlations between task performance and movement measures showed significant positive relationships between movement, number of utterances, and number of differences found, indicating a relationship between movement and task performance consistent with my hypotheses.

Movement Coordination

Hand. At the hand, there was a greater amount of overall coordination when both participants were free to move versus when one was restrained or when both were restrained, and this coordination was more stable when both were free compared to when one was

restrained and the other was not. While this, at first blush, may seem to be an arbitrary finding, in that the asymmetry in possible body configurations imposed by the methodology would almost demand a lower degree of coordination in the FR condition, it is interesting to note the significantly higher degree of shared configurations in the FF condition as compared to the RR condition. Importantly, since the state spaces of individuals were reduced to a smaller volume in the latter condition, it is reasonable to assume the shared configurations may be higher in the RR condition. Indeed, the fact that the deterministic structure of coordination was higher in RR than in FF speaks to the likelihood of finding greater recurrence in the former condition, since a greater amount of deterministic structure means the shared dynamics are reliably revisiting the same regions of their phase spaces. However, the fact that participants actually exhibited a greater amount of overall shared configurations when they had the additional degrees of freedom suggests that being able to move the outer effectors enhances the coordinative capabilities of individuals, though at the cost of some structural stability of the coordination.

Waist. The coordination of movement at the waist was also affected by restraining hand motion. This is not surprising, as supra-postural tasks have been shown to impact postural sway. For example, simply adding visual inspection (Bardy et al., 2000) or the act of articulation (Gardner et al., 1999) to the task of standing is enough to substantially alter postural sway. In the current study, I found that both the deterministic structure and the overall stability of coordination at the waist were higher when both individuals were restrained as compared to when only one individual was restrained. This suggests that asymmetry in body configurations influence postural sway coordination, with similar constraints yielding a more stable and structured coordination than constraints which are dissimilar.

Head. At the head, the overall amount of coordination between individuals was higher when both members of a dyad were able to move their hands compared to when one person was restrained. Further, coordination of head movement was more stable when both participants were free compared to when both were restrained and when one participant was restrained and the other was free to move. Consistent with my hypothesis, these results echo the findings of differing coordination patterns found at the hand for different degrees of restraint, with the addition that coordination was more stable in FF compared to RR.

Gaze Coordination

When the gazes of individuals were evaluated, the asymmetric degree of restraint had a negative impact on the deterministic structure of shared looking patterns as compared to when both individuals were unrestrained. Also, the overall stability of shared looking patterns was higher when both individuals' hands were free as compared to when one person was restrained, as well as compared to when both individuals were restrained. This means that being able to move one's hands significantly impacted the manner in which conversing individuals coordinated their gaze to visually survey environmental structure, with a restraint on the bodily degrees of freedom negatively impacting their ability to do so. Further, JRQ analysis showed that the overall likelihood of finding simultaneous coordination of the body and coordination of gaze is greatest when participants are unrestrained. This demonstrates that bodily coordination is more aligned with gaze coordination when participants are unrestrained.

Relationship between Movement, Coordination, and Communication

Although the restraint manipulation did not show a significant influence on task performance in terms of numbers of differences found, correlation analysis showed several significant relationships between speech, movement, coordination, and task performance

consistent with my hypothesis. Overall movement measured at the hand, waist, and head of person 1 were positively correlated with the number of differences found, meaning that for groups where person 1 moved more, more differences were found in the puzzles. The total number of utterances made by person 1 and by the dyad on average was also positively correlated with the number of differences found. It is interesting to note is that, while a variety of measurements taken at person 1 correlated significantly with task performance, the overall movement and number of utterances of person 2 did not. This asymmetry in relationships is consistent with the asymmetry in restraints placed on the two individuals. Also noteworthy is that the amount 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—which has been observed in previous studies (Condon & Ogston, 1971; Newton, 1994).

Additionally, the positive correlation between differences found and amount of utterances may explain why there was no effect of restraint on differences found for the ANOVA, as there was a good deal of within and between group variability with respect to amount of utterances. For example, more than half of the individuals labeled as person 1 showed a range of over 20% of their mean amount of utterances at the individual trial level within the conditions, while just under half met the same criterion for person 2. This wide range of within-group variability of a measure shown to affect task performance may have mitigated the influence of restraint. One possible method to control for within group variability in future experiments is to impose stricter restraints on hand movement, since the aprons allowed a certain amount of freedom, and some participants were observed moving their hands back and forth in the pockets while they were in the restrained condition.

Finally, despite there being significant relationships between overall movement and task performance, there were no significant relationship between coordination patterns and the number of differences found. 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, thus 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 research. However, once alignment has been reached and individuals share a common perspective, what becomes of significant importance are the residual asymmetries that represent the information available to one person which is hidden from the other. In order to share this information, the alignment must be broken and asymmetry introduced, which, according to an embodiment perspective, would indicate a break in the higher order coordination pattern existing between the two individuals. Thus, while it is important to coordinate movement to reach a common understanding, for the given task constraints, it may be equally important to break this coordination. Thusly, it could be expected that the formation and breaking of coordinative patterns would offset each other, resulting in null results when coordination patterns are assessed across entire trials.

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