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RESEARCH ARTICLE

Visual influences on postural and manual interpersonal coordination during a joint precision task

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Abstract We investigated whether the interpersonal postural coordination that occurs during a joint supra-postural, manual precision task is driven by the constraints of the task, or, instead results from visual entrainment to the movements of a co-actor. Participants were instructed to coordinate their finger movements under conditions where participants could see others' whole-body movements or could only see the results of the other's actions. Participants' finger and torso movements were recorded. Coordination was quantified using cross-recurrence quantification analysis measures. Interpersonal coordination was enhanced by, although it did not depend entirely upon, visual information about the co-actor's body movements.

Keywords Interpersonal coordination · Cross-recurrence quantification analysis (CRQA) · Joint action · Postural control

Introduction

Interpersonal coordination often occurs during joint action. For example, people interact synergistically when lifting objects together (Bosga and Meulenbroek 2007), and when people converse, they exhibit motor synchrony—they mirror the spatiotemporal patterns of each others' movements, either intentionally or unintentionally (Chartrand and Bargh 1999; Condon and Ogston 1966; Condon and Sander 1974; Fowler et al. 2008; Kendon 1970; Lakin and Chartrand 2003; Newtson 1994; Shockley et al. 2003). Interpersonal coordination is sometimes an explicit goal of joint actions such as dancing and may be necessary for successfully completing joint lifting or other joint motor tasks. But even during activities for which interpersonal movement coordination seems incidental, like conversation, motor coordination embodies the social, cognitive, and linguistic coordination required for effective communication (Bernieri et al. 1994; Dale and Spivey 2006; Knoblich and Sebanz 2006; LaFrance 1979, 1982; Marsh et al. 2009; Richardson et al. 2007a, 2008; Sebanz et al. 2006; Shockley et al. 2009). It is important to understand the fundamental mechanisms and processes that facilitate interpersonal coordination in order to better understand motor coordination in its own right and also because interpersonal motor coordination might promote or at least index social, cognitive, and linguistic interpersonal coordination. An important issue regards the means by which two actors' movements become *coupled* (reciprocally linked), since the nature of the coupling can influence the nature, strength, and stability of interpersonal coordination. The focus of the present study was the role of visual perception in achieving this coupling and, in particular, the importance of *task-relevant* versus *task-irrelevant* visual information on interpersonal coordination.

In the context of interpersonal coordination, coupling refers to how two people become linked or connected by some medium that permits their movements to influence and constrain one another. *Mechanical* coupling, for example, occurs when two people lift an object together and each person's lifting forces influence the other's actions

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(e.g., Bosga and Meulenbroek 2007). Besides joint lifting, few studies have focused on the effects of mechanical coupling on interpersonal coordination. Harrison and Richardson (2009) mechanically linked two individuals by means of a foam block attached to each person's torso and had the coupled dyad walk while so linked. Mechanically coupled dyads spontaneously produced gait patterns that are typical of quadrupedal animals and that are not seen in human bipedal gait in the absence of mechanical coupling.

A second type of coupling is *informational* or *perceptual* coupling. While it is possible for informational coupling to occur via different perceptual modalities, research in interpersonal coordination has tended to focus on visual coupling (e.g., Lopresti-Goodman et al. 2008; Schmidt et al. 1990; Schmidt and O'Brien 1997; Richardson et al. 2005, 2007a, Varlet et al. 2011). For example, in rhythmic coordination tasks where movement coordination is an explicit joint goal, two people can successfully coordinate their limb movements if they can see each other's movements (Schmidt et al. 1990, Black et al. 2007). Rhythmic limb movements are unlikely to become coordinated when participants cannot see each other, even if they are interacting with each other in some meaningful fashion such as conversing (Richardson et al. 2005), suggesting that visual (or more broadly, perceptual) coupling is necessary for interpersonal coordination of rhythmic limb movements. Moreover, in cases when there is no explicit joint goal or intention to coordinate, spontaneous, unintended interpersonal coordination of rhythmic limb movements can occur by way of visual coupling (Richardson et al. 2005, 2007a; Schmidt and O'Brien 1997).

Visual coupling is also sufficient to promote unintended interpersonal coordination of postural sway (the complex, low amplitude fluctuations of the position of the body's center of mass) between people (Varlet et al. 2011). However, visual coupling is not necessary for some types of interpersonal postural coordination. Postural coordination spontaneously occurs between two participants conversing with each other to jointly solve a puzzle task (Shockley et al. 2003, 2007; Stoffregen et al. 2000). In these studies, the coordination occurred and was equally strong regardless of whether participants could see each other, in contrast to the findings for rhythmic limb movement coordination (Lopresti-Goodman et al. 2008; Richardson et al. 2005; 2007b; Schmidt and O'Brien 1997).

Rather than being linked by visual coupling, the conversing participants in Shockley et al. (2003, 2007) and Stoffregen et al. (2000) were coupled by the exchange of linguistic information—*dialogical coupling* (Fusaroli et al. 2014)—and coordination was influenced by the cognitive and perceptual-motor constraints imposed on their behavior. When people converse, they talk in a temporally structured fashion (e.g., turn-taking), they use similar speech rhythms, they tend to match vocal intensity, they coordinate syntactically, and so on (Capella and Planalp 1981; Dale and Spivey 2006; Natale 1975; Street 1984). Participants in those studies also faced similar perceptual and biomechanical task demands: Both participants attended to a small visual target and may have performed similar postural modulations that occur to facilitate visual task performance (e.g., Stoffregen et al. 1999, 2000). Further studies showed that interpersonal coordination during conversation tasks is modulated by visual factors other than sight of the conversational partner (e.g., picture puzzle size and distance, Stoffregen et al. 2013), by articulatory constraints (similarity of the words spoken and their stress patterns, Shockley et al. 2007), and by biomechanical factors (standing on a rigid surface versus nonrigid surface, Stoffregen et al. 2009).

Thus, the literature shows that visual coupling is, on the one hand, necessary to promote intentional coordination of rhythmic movements and is sufficient to promote spontaneous coordination of rhythmic movements (e.g., Schmidt and O'Brien 1997) and postural sway during joint visual tracking tasks (Varlet et al. 2011). On the other hand, for interpersonal postural coordination during conversational tasks, vision of the task partner is not necessary nor does it enhance interpersonal coordination when participants are so engaged. Is the latter outcome true for other types of interpersonal postural coordination?

The absence of an effect of visual coupling in studies of interpersonal conversational tasks could be due the unique speech and articulatory constraints imposed by conversation, and it could still be the case that visual coupling promotes increased interpersonal postural coordination (whether intended or spontaneous, e.g., Varlet et al. 2011) during other types of joint tasks for which visual feedback about the task partners' actions plays a more directly important role. The role of vision is complex and is likely to depend on many factors, including the nature of the task itself (i.e., whether the joint task goal requires information about a co-actors movements) and the nature of the visual information that is available to the actors. The latter issue was the primary focus of the present study.

During a joint task, co-actors may be able to see partner movements that are directly relevant to success of the joint ask—*task-relevant visual information*—but in other cases, they may see partner movements that are only indirectly related or even entirely incidental to the joint task—*task-irrelevant visual information*. During coordination of rhythmic limb movements, co-actors must have task-relevant visual information about their partner's oscillating limb in order to intentionally coordinate, and, moreover, such task-relevant information is sufficient to support unintentional coordination (e.g., Schmidt and O'Brien 1997) whether or not participants explicitly focus their vision on task-relevant partner movements or whether they occur in the visual periphery (Richardson et al. 2008).

Ramenzoni et al. (2011) studied a joint perceptual-motor task that required one actor to hold a pointer inside a target ring held by another actor. Task-relevant visual information regarding each participant's hand movements was necessary to achieve the intended joint goal, and it was always available. Participants could also see each other's full body motions at all times—information that might be considered task-irrelevant since motions of other body segments related only indirectly to task performance. As might be expected, participants coordinated their hand movements to perform the precision task successfully. Interpersonal postural coordination also occurred. At issue is the origin of the latter effect.

The interpersonal postural coordination could have emerged as a spontaneous consequence of visual coupling since participants could see each others' hand movements (task-relevant information) and postural sway (task-irrelevant information). Alternatively, it may have been an incidental consequence of participants' efforts to control their hand and arm movements. Precision manual activity can be facilitated by constraining postural sway (Riley et al. 1999) and by reciprocally controlling hand movements and postural sway in a way that takes into account their mutual influences (i.e., by *intrapersonal* hand-torso coordination). When participants in Ramenzoni et al. (2011) exhibited greater *inter*personal hand coordination, they also exhibited greater *intra*personal coordination between the hand and torso. This suggests that interpersonal postural coordination could have been driven by the task demand to precisely coordinate hand movements. That is, participants were required to coordinate their hand movements, and this could have incidentally given rise to interpersonal postural coordination because of the biomechanical linkages between each person's own hand and torso.

Ramenzoni et al. (2011) included a manipulation of the stability of stance in order to further elucidate the role of biomechanical task demands. Tasks that require one to stand in order to achieve other types of behavioral goals, such as the precision manual task in Ramenzoni et al. and in the present experiment, necessitate a functional integration of postural control and manual control. Such synergistic integration is achieved at the intrapersonal scale in terms of coordination between an actor's hand and torso movements. Decreasing postural stability could influence intrapersonal coordination, and this could, in turn, influence interpersonal coordination. In accordance with that expectation, Ramenzoni et al. found that decreasing participants' postural stability by having them adopt difficult stances produced a cascade of intrapersonal and interpersonal effects. Participants' hand and torso movements were more variable in a difficult tandem (heel-to-toe) stance, and their intrapersonal hand-torso coordination was reduced when they adopted that stance compared to a more stable (feet shoulder-width apart) stance. The tandem stance condition also resulted in decreases in the overall *amount* of interpersonal postural coordination (although it was associated with an increase in the *stability* of the coordination). The amount of interpersonal postural coordination was greater when both participants adopted a more stable shoulder-width stance and intermediate when one participant stood in the tandem stance and the other in a shoulder-width stance.

Several findings in Ramenzoni et al. (2011) point toward an influence of both task and biomechanical factors on interpersonal postural coordination. Similar task demands could have led participants to produce similar body movements, and disruptions to postural stability impaired interpersonal coordination. However, visual coupling may have also been a contributing factor to the emergence of postural coordination since their participants always had access to both task-relevant and task-irrelevant visual information about their partner's motions. The relative contributions of biomechanical and visual factors therefore cannot be determined from the results of Ramenzoni et al.

The present study sought to clarify this issue and thus contribute to the theoretical understanding of the role of visual coupling in interpersonal motor coordination during joint action. Specifically, this study sought to understand any differential effects of type of visual coupling on interpersonal coordination of hand movements (which was required for task success) and postural sway (which was not obviously required for task success) in a joint perceptual-motor task. We either provided participants with full view of their task partner's movements or restricted visual information to just the task-relevant information necessary to achieve the goal of the joint precision task. Following Ramenzoni et al. (2011), we also included a manipulation of postural stability. We expected interpersonal manual coordination to occur in both visual conditions and for all postural stability conditions because that coordination was required for successful task performance. The key measure of interest was interpersonal *postural* coordination, since that was not absolutely required for successful task performance but was nonetheless observed for the similar task in Ramenzoni et al. If interpersonal postural coordination is driven by the motor or biomechanical demands of joint actions, it should occur independent of visual information of another person's whole-body movements and should be reduced when participants' postural stability is decreased. If postural coordination is instead an automatic consequence of visual coupling, postural coordination should only occur when participants can fully see each other. Of course, both visual entrainment and task demands could be important, in which case our manipulation of visual information should

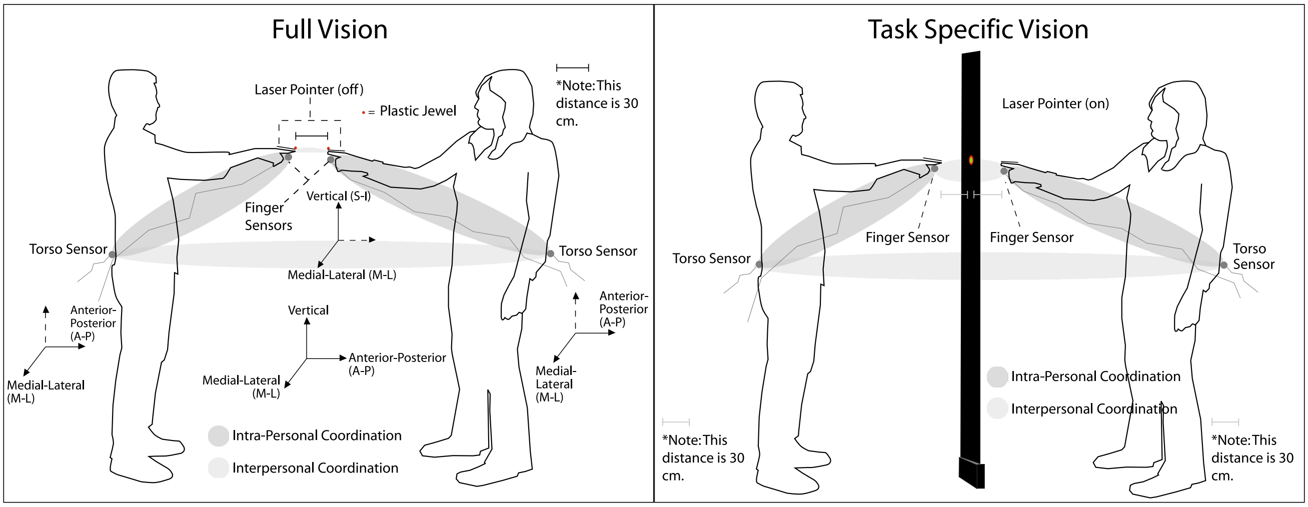

Fig. 1 Illustration of experimental set-up

have graded rather than all-or-none effects on interpersonal postural coordination. Furthermore, if interpersonal coordination was independent of vision but dependent on the stance manipulation, it would provide further evidence for the notion that shared task demands give rise to interpersonal coordination more so than visual entrainment.

Methods

Participants

Fourteen pairs ($N = 28$; 5 men, 23 women) of right-handed participants were recruited. Seven graduate students and twenty-one undergraduate students, all naïve to the specific hypotheses of the investigation, participated in the study. Undergraduates received course credit for their participation. All participants reported normal or corrected-to-normal vision and no history of neuromuscular disorders or recent injuries. Informed consent was obtained.

Apparatus

A Polhemus Fastrak motion capture system (Polhemus Corporation, Colchester, VT) with custom software recorded movement (30 Hz) from each participant's right index fingertip and lumbar torso. Adhesive tape was used to attach motion sensors to those body segments. In one condition, a black fabric screen was suspended from the ceiling to hang between the participants. A laser pointer was attached to each participant's right index finger using adhesive tape. One laser pointer projected a green dot and the other a red dot. A red plastic "jewel" (1 cm diameter) was also attached to each participant's right index fingertip. The laser pointers were used for the *task-specific vision* (TS) condition (task: align the projected dots on the black screen). The jewels were used in the *full vision* (FV) condition (task: align the jewels with each other); given that the laser pointers could not be used for safety reasons in the FV condition, the use of the jewels made the TS and FV conditions more similar (both involved aligning a colored dot of sorts) than would have been the case if participants pointed with unadorned fingers in the FV condition. Also, this helped control for differences in motor control known to occur when actors focus attention explicitly on body segments and their motion as opposed to focusing on some external attachment to a body segment or an external consequence of motion (e.g., Wulf et al. 2004).

Procedure

All procedures were approved by the University of Cincinnati IRB. Participants stood barefoot facing one another and extended their right arm and index finger (Fig. 1). The task required participants to coordinate fingertip movements in order to align either the plastic jewels placed on their fingertips (FV condition) or the laser pointer dots projected onto the black screen (TS condition) and maintain that alignment for the duration of each 60 s trial. In both conditions, the required alignment was in the medial–lateral (ML) and superior–inferior (SI) planes. Participants stood with their fingertips approximately 30 cm apart in the FV condition or with approximately 30 cm between the fingertip and screen in the TS condition. Participants were not instructed to maintain that distance (AP movements were not restricted by instructions) but were not allowed to step forward or backward. In the TS condition, the screen was placed between participants to remove visual information about the position and configuration of the partner's body. For safety reasons, during the FV condition the laser pointers were turned off. In the TS condition, the laser pointers were turned on and participants pointed to project the beams onto the screen. Each participant could see the projections of both beams on the screen and could distinguish their beam from their partners by color. Participants were instructed to align the laser pointer dots in the same way they aligned the jewels in the FV condition (in the ML and SI planes). In both conditions, task-relevant information (relative position of the laser dots or the fingertip jewels) was visible to participants, but the partner's body was only visible in the FV condition. An experimenter monitored performance to ensure participants complied with task instructions. Trials during which participants had long or frequent stretches of misalignment were stopped and repeated (<2.5 % of all trials).

We manipulated postural demand across four stance conditions (Ramenzoni et al. 2011): Both participants in *stable* (feet shoulder-width apart) stance, two *mixed* conditions in which one participant adopted the stable stance while the other adopted an unstable (heel-to-toe stance with the dominant foot forward) stance, and both in the *unstable* stance. Although this unstable condition was used, there were no sudden perturbations or other efforts to disrupt coordination. In total, there were eight conditions. Participants performed two trials per condition in randomized order. The two mixed conditions—each participant stood in one stance in the first condition and then in the other in the second—were averaged to yield a single mixed condition for data analysis.

Data analysis

Time series of each actor's torso and fingertip position were analyzed to quantify coordination. The first and last 3 s were trimmed from each time series to eliminate transients. The remaining data were analyzed using cross-recurrence quantification analysis (CRQA; Marwan et al. 2002; Shockley 2005; Shockley et al. 2002; Webber and Zbilut 2005; Zbilut et al. 1998) to measure interpersonal coordination (of finger and of torso movements between members of a pair) and intrapersonal coordination (of finger and torso movements within a person). CRQA measures the co-evolution of two time series along their (reconstructed) attractors. The overall degree of coordination and coordination stability is measured, respectively, by *%cross-recurrence* and *maxline*. CRQA is a suitable method as it measures coordination *between* signals; in contrast, recurrence analysis on time series of individual body segments (or on the difference of any two segment position time series) does not afford straightforward interpretations in terms of the amount or stability of coordination between the two actors. CRQA also does not assume linearity, stationarity, or any particular distribution, which makes CRQA useful for analyzing complex or irregular time series.

CRQA (for details, see Shockley 2005) begins by reconstructing the time series' underlying attractors (Abarbanel 1996). The optimal embedding dimension was selected using global false nearest neighbors analysis (Kennel et al. 1992). The time delay was determined as the first minimum of the average mutual information function (Cao 1997). These methods indicated embedding dimension = 3 and time delay = 5 samples (.17 s). CRQA proceeds by then determining how often (*%cross-recurrence*) and for how long (*maxline*) the two trajectories share the same locations (i.e., fall within a tolerance radius, selected for the present data using the procedures in Shockley 2005 as 20 % of the mean distance separating data points) in reconstructed phase space. Randomly shuffled versions of each time series were created to destroy the sequential dependence in the data, and the results of CRQA performed on those shuffled data were compared to the original data. The hypothesis for the latter analyses was that random shuffling would significantly reduce the coordination measures compared to the original data, an outcome that would indicate that any coordination identified in the original time series was in fact related to the temporal order of the data.

If task constraints were driving unintended interpersonal postural coordination, then *%cross-recurrence* and *maxline* values for torso movements were expected to be similar across TS and FV conditions. On the other hand, if the postural coordination was *solely* driven by visual information from seeing another person's body movements, then we expected (a) *%cross-recurrence* and *maxline* values to be significantly reduced in the TS compared to FV condition, and (b) *%cross-recurrence* values of randomly time shuffled series to not differ from *%cross-recurrence* values of the original times series, indicating a lack of actual coordination when participants could not see each other in the TS condition.

Results

Interpersonal coordination

The coordination measures were submitted to 2 (vision) × 3 (stance) analyses of variance (ANOVAs). *%cross-recurrence* and *maxline* were computed and analyzed for torso and finger movements. Figure 2 provides representative cross-recurrence plots for interpersonal postural coordination in the stable stance condition showing the FV and TS conditions and their corresponding time series.

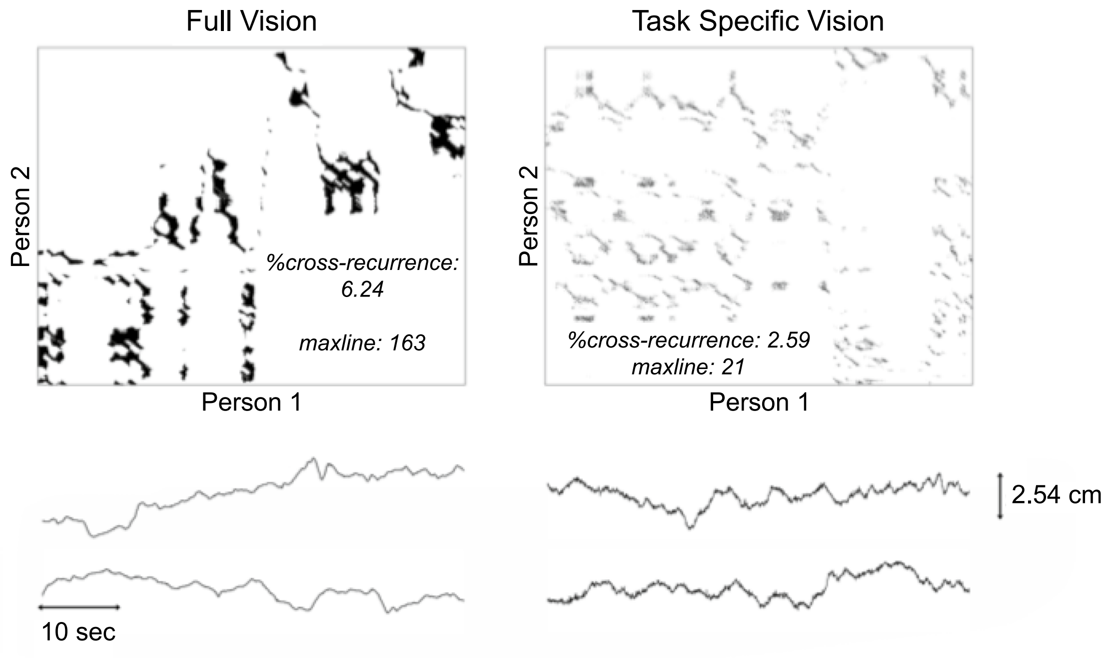

Fig. 2 Representative cross-recurrence plots (*top panel*) for interpersonal postural coordination in the stable stance condition showing the FV (*left*) and TS (*right*) conditions and corresponding time series. Consistent with the overall pattern of results, more recurrence points are apparent in the FV condition than the TS condition

Interpersonal postural coordination. %cross-recurrence and *maxline* were analyzed for torso movements in the mediolateral (ML) and anteroposterior (AP) planes. As seen in Fig. 3, *%cross-recurrence* differed significantly between the FV and TS conditions for both ML [$F(1,13) = 20.45$, $p < .001$] and AP [$F(1,13) = 74.83$, $p < .001$] motions. There was greater interpersonal postural coordination in the FV condition (ML: mean ± SD = 3.44 ± 2.81; AP: 4.19 ± 3.12) than in the TS condition, when they could not see each other's whole-body movements (ML: 1.93 ± 2.73; AP: 1.43 ± 2.07). Stance did not significantly affect *%cross-recurrence* (ML: $p = .60$; AP: $p = .41$), nor were any significant interactions observed (ML: $p = .90$; AP: $p = .88$).

Maxline differed significantly between the FV and TS conditions for both ML [$F(1,13) = 19.30$, $p < .001$] and AP [$F(1,13) = 17.20$, $p < .01$]. More stable postural coordination occurred when partners could see one another completely in the FV condition (ML: 58.24 ± 60.28; AP: 75.63 ± 74.00) than in the TS condition (ML: 21.78 ± 41.29; AP: 36.90 ± 60.15). Stance did not significantly affect *maxline* (ML: $p = .33$; AP: $p = .70$), nor were there any significant interactions (ML: $p = .82$; AP: $p = .52$).

Interpersonal finger coordination. %cross-recurrence and *maxline* were analyzed for finger movements in the ML and superior–inferior (SI) planes, which were the task-relevant movement planes for the pointing task. Variations in the distance between fingertips in the AP plane were not constrained by task instructions so AP was not analyzed.

%cross-recurrence differed significantly between the FV and TS conditions for finger movements in the ML plane [$F(1,13) = 5.92$, $p < .05$; FV: 3.83 ± 1.84, TS: 2.93 ± 3.02] but not for finger movements in the SI plane ($p = .38$). There was a significant effect for stance on *%cross-recurrence* in the SI plane [$F(2,26) = 4.09$, $p < .05$], where *%cross-recurrence* decreased with increases in postural demand, from both-stable (3.73 ± 3.32) to mixed (3.46 ± 3.66) to both-unstable (3.05 ± 2.50), although post hoc analysis did not show any significant differences between stances. There was no effect of stance for ML ($p = .23$), and no vision × stance interaction for either ML ($p = .13$) or SI ($p = .76$).

Maxline differed significantly between FV and TS conditions for ML [$F(1,13) = 6.35$, $p < .05$], indicating more stable finger coordination in the FV (66.37 ± 41.29) than in the TS (45.68 ± 74.75) condition. There was no significant effect of vision for SI ($p = .87$). Stance was not significant for *maxline* for SI ($p = .06$) or ML ($p = .35$). No vision × stance interaction was found for either ML ($p = .13$) or SI ($p = .23$).

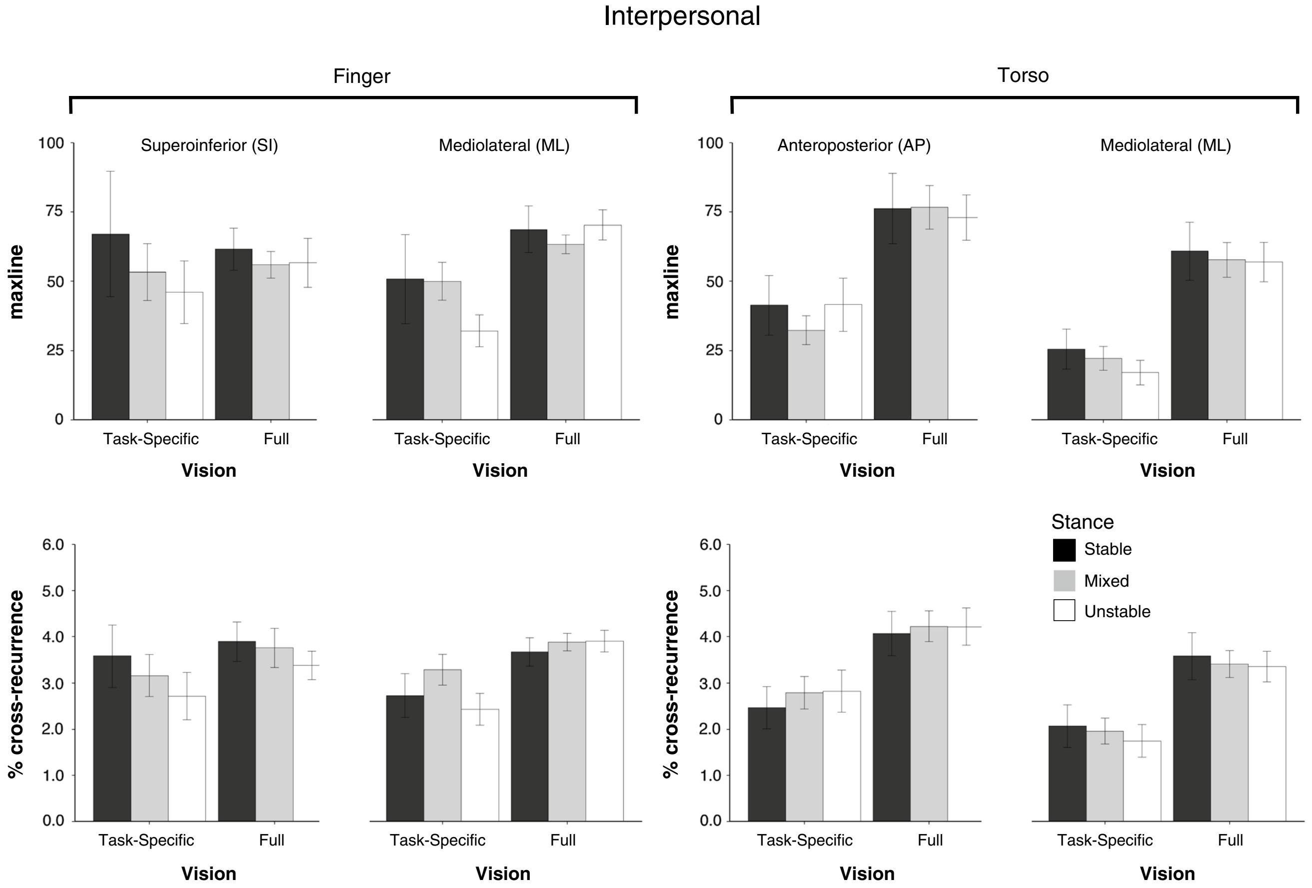

Fig. 3 *Bar* plots depicting means and standard errors of %cross-recurrence and maxline values under different stance and vision conditions for *interpersonal* coordination

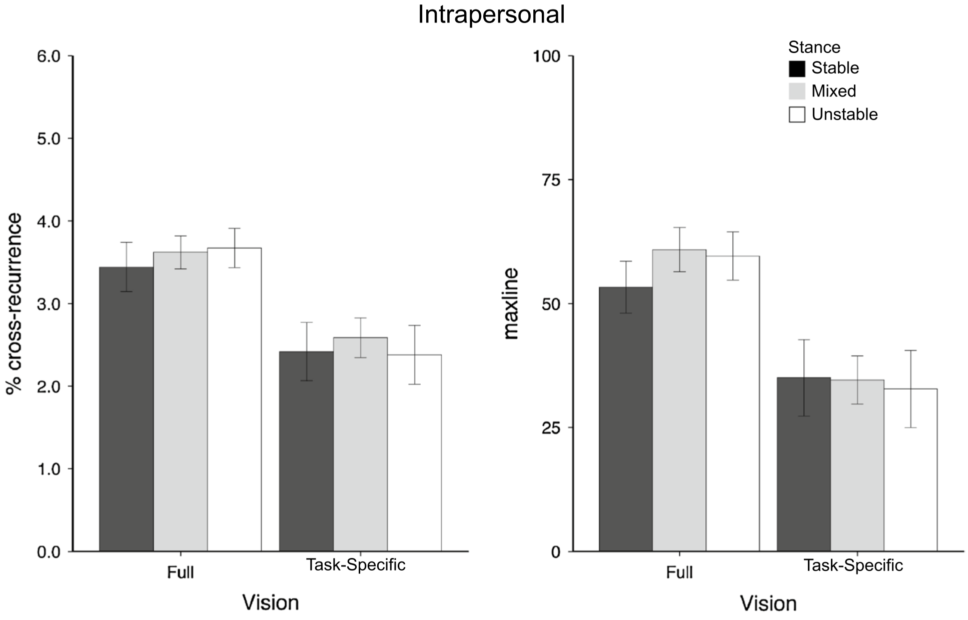

Fig. 4 *Bar* plots depicting means and standard errors of %cross-recurrence and maxline under different stance and vision conditions for *intrapersonal* coordination between and finger and torso

Intrapersonal coordination

As seen in Fig. 4, participants exhibited greater intrapersonal coordination [*%cross-recurrence*: $F(1,13) = 12.71$, $p < .01$] and greater coordination stability [*maxline*: $F(1,13) = 10.76$, $p < .01$] in the FV [*%cross-recurrence*: 3.59 ± 2.65; *maxline*: 58.68 ± 55.23] than in the TS (*%cross-recurrence*: 2.49 ± 3.36; *maxline*: 34.25 ± 70.31) condition for ML (the only task-relevant plane common to torso and finger movements). No effect for stance (*%cross-recurrence*: $p = .71$; *maxline*: $p = .66$) nor an interaction (*%cross-recurrence*: $p = .79$; *maxline*: $p = .50$) was found.

Consistency of results

For interpersonal postural coordination, *%cross-recurrence* was greater in the FV than TS condition for 13/14 dyads in ML and 12/14 dyads in AP. *Maxline* was greater for 13/14 dyads in both AP and ML. For interpersonal finger coordination, *%cross-recurrence* was greater in the FV condition for 9/14 dyads in SI and 11/14 dyads in ML, and *maxline* was greater in the FV condition for 11/14 dyads in SI and 12/14 dyads in ML. Intrapersonal coordination was also consistent across participants with higher *%cross-recurrence* (23/28 participants) and higher *maxline* (26/28 participants) in the FV than TS condition.

Surrogate analysis

Surrogate analyses were performed to verify that the coordination measures were not artifacts (Theiler et al. 1992). Randomly shuffled versions of each time series were created to destroy the sequential dependence in the data while leaving the data distribution unaltered. The shuffled time series effectively serve as a baseline to compare with the *%cross-recurrence* values found in the experiment. The hypothesis for these analyses was that random shuffling would significantly reduce the coordination measures compared to the original data because it would destroy the temporal sequencing of the data points. As expected, *%cross-recurrence* for the surrogate time series was significantly lower than for the original time series, indicating the degree of postural and finger coordination (time-dependent co-evolution of the two participants' time series) in the original data was valid (all $p < .01$). For the vast majority of surrogate series, *maxline* was undefined (there were no diagonal lines in the cross-recurrence plot), so we did not analyze *maxline* further in the surrogate analyses. Surrogate analyses confirmed that the coordination measures reflected genuine properties of the co-evolution of the time series across all conditions.

Discussion

Consistent with prior research (Ramenzoni et al. 2011, 2012), spontaneous interpersonal postural and manual coordination occurred between people engaged in the joint task. Coordination of finger movements was expected, as it was required to perform the task. Our primary questions were whether interpersonal *postural* coordination would emerge when the only visual information that was available was very specific to the effectors involved in performing the task, whether interpersonal postural coordination was a function of task constraints (i.e., task performance requires participants to coordinate their postural sway), or whether interpersonal postural coordination in the present task was an example of spontaneous visual entrainment (e.g., Richardson et al. 2007b). The answer seems to be "all of the above." Seeing the partner's body during the task was not necessary for the occurrence of interpersonal postural coordination (the coordination measures "passed" the surrogate test in the TS condition), but the degree of interpersonal postural coordination did increase when actors were able to see one another in the FV condition compared to the TS condition. This contrasts with results showing that vision of the partner does not increase interpersonal postural coordination during conversational tasks—where the task itself does not have an immediate visual goal and where coordination seems to be shaped almost exclusively by factors such as structured articulation rather than by visual coupling (Shockley et al. 2007, 2003). One of the important conclusions that we can draw from the present results, therefore, is that the effects of vision on spontaneous emergence of interpersonal postural coordination during joint action appear to depend on the nature of the joint action. For tasks in which there is a visual goal, it is possible that the postural coordination results both from task-relevant visual information about goal-directed movements and spontaneous coupling resulting from merely seeing the task partner. For tasks where visual information about the partner is not task-relevant like in the conversational task, the ability to see one's partner may have little to no additional effect on the spontaneous emergence of postural coordination between co-actors.

The greater degree and stability of interpersonal postural coordination when participants could see each other in the FV condition might be an explicit, adaptive response that served to facilitate performance of the joint task. Establishing postural coordination could have made interpersonal finger coordination—which was more directly related to the goal of the joint task—less effortful or otherwise easier. Similar adaptations are known to occur for individual performance of precision manual tasks. For example, people tend to reduce postural sway variability when confronted with the demands of a precision manual task (e.g., Riley et al. 1999). The somewhat unexpected finding that finger coordination was more pronounced in the FV condition supports this possibility. The possibility is also supported by the intrapersonal (finger–torso within each participant) coordination results, which shows that full vision increases the degree and stability of intrapersonal coordination.

The intrapersonal coordination results, which paralleled the interpersonal coordination results, could additionally reflect the nested nature of interpersonal and intrapersonal coordination (Ramenzoni et al. 2011). There is potentially a circularly causal relationship between the two, where *inter*personal coordination might scaffold upon *intra*personal coordination, and when there is a higher-order task goal involving interpersonal coordination, then interpersonal coordination can constrain intrapersonal coordination (Bosga et al. 2010). When two people exhibit interpersonal coordination of both finger and torso motion, this is likely to impose coordination between the finger and torso at the intrapersonal level. However, at the same time, if at the intrapersonal level an actor coordinates finger and torso motion, then it may become more likely for interpersonal coordination of both finger and torso segments to occur. On the other hand, the lesser degree of *inter*personal coordination in the TS condition might have imposed weaker constraints on the coordination between each individual's finger and torso movements, leading to a lesser degree of *intra*personal coordination. Thus, a second important contribution of this work is to shed additional light on the nested relationship between intrapersonal and interpersonal coordination processes.

Stance did not significantly affect interpersonal postural coordination or intrapersonal coordination. Interpersonal finger coordination as indexed by *%cross-recurrence* was greater when both participants adopted the more stable stance, but was diminished when at least one person stood in the unstable stance, consistent with the hand coordination results of Ramenzoni et al. (2011). This indicated that the more stable posture afforded better coordination of the effectors, and this was independent of whether participants received task-specific visual information or had full vision of their partners. However, the paucity of stance effects in the present study contrasts with the abundance of stance effects in Ramenzoni et al. In their study, less stable stances were associated with greater effector variability, reduced levels of intrapersonal coordination, and, for interpersonal postural coordination, a lesser overall degree of coordination but increased stability of the coordination. There were some subtle differences in the tasks in the two studies that may have contributed to the differences in results. For instance, in Ramenzoni et al., one person held a target circle and one person held a pointer object, and thus, their participants performed *complementary* actions, whereas in the present study participants' roles were more similar to each other. In addition, full vision was always available in their study. Despite these differences, however, the lack of stance effects in the present study was surprising given the overall similarity of the experimental tasks in our study and in Ramenzoni et al.

Interpersonal postural coordination during the precision manual joint task studied in this experiment did not require seeing the task partner and thus does not appear to be just an automatic form of visual coupling. It is therefore possible that the explicit goal of interpersonal finger coordination is driving the interpersonal postural coordination in this supra-postural task. Since posture assumes a supportive role to achieve the intended joint goal (finger alignment), the same kind of postural constraints may be operating on each individual in the dyad. As a consequence, interpersonal postural coordination emerges as a form of task-driven coordination. Another possibility is that the postural movements share common boundary conditions within which movements could evolve. Nevertheless, interpersonal postural coordination was enhanced by full vision of the task partner's whole-body movements, so neither was the coordination solely derivative of the need to perform similar manual actions concurrently in order to complete the task successfully. Visual coupling may have enabled interacting participants to facilitate task performance by stabilizing postural sway relative to each other and by stabilizing manual performance relative to their own torsos and to the other participant's effector. Enhanced visual information in FV may have constrained the many degrees of freedom involved in the interpersonal finger alignment task to form a synergy across interpersonal and intrapersonal body segments (Riley et al. 2011). However, we do not claim that vision is "special" in the sense that it is necessarily superior to other modalities in facilitating interpersonal coordination. Interpersonal coordination could be achieved by coupling in a variety of modalities including haptics (Reed et al. 2006; van der Wel et al. 2011) and audition (Demos et al. 2012).

The basic processes and mechanisms that support coordination during joint action are only beginning to be understood. It is important to continue to develop a more refined understanding of these issues, for both theoretical and practical reasons. On the practical side, a comprehensive understanding of interpersonal coordination could have implications for phenomena as far-ranging as social interactions involving children with autism (Knoblich and Sebanz 2006) to performance of team cognitive tasks in military command and control (Tollner-Burngasser et al. 2010). It is important to understand the role of visual information for such applied problems. For example, if interpersonal motor coordination embodies the cognitive coordination required for successful joint or team performance (Shockley et al. 2009), then understanding how visual information affects interpersonal coordination could have implications for improving team performance. For example, to maximize performance during team military command and control tasks, does the physical workspace need to be arranged so that team members can see each other, or do task-specific factors, such as when team members jointly attend to the same region of the task space, suffice to promote cognitive coordination that could enhance performance? While the present task speaks more directly to relatively simple real-world behaviors involving manual coordination, such as pouring a drink into a glass another person is holding or handing a small object from one person to another, the underlying principles may apply more generally to tasks involving a balance between visually mediated interaction and shared motoric constraints.

Conclusion

When only task-specific visual information was available, participants' finger movements were coordinated in order to achieve the task goal of aligning the laser pointer dots. During the FV condition, when the task-relevant information about relative finger position was accompanied by full vision of the task partners' body motions, interpersonal fingertip coordination was enhanced compared to the TS condition. Further, interpersonal postural coordination, which was not required for task performance, seemed to emerge spontaneously during performance of this joint action and was also enhanced in FV condition compared to TS condition. This pattern of results suggests, at least for this interpersonal precision manual task, that similar task constraints and biomechanical factors are not the sole driving factors behind interpersonal postural coordination. Interpersonal postural coordination instead appeared to emerge spontaneously as a result of spontaneous visual entrainment. This result contrasts with findings from interpersonal conversational tasks (e.g., Shockley et al. 2003). Further research will be required to identify the specific factors that moderate the influence of visual coupling on interpersonal postural coordination.

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