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Social Postural Coordination

Manuel Varlet, Ludovic Marin, Julien Lagarde, and Benoît G. Bardy
Montpellier-1 University

The goal of the current study was to investigate whether a visual coupling between two people can produce spontaneous interpersonal postural coordination and change their intrapersonal postural coordination involved in the control of stance. We examined the front-to-back head displacements of participants and the angular motion of their hip and ankle during a visual tracking task performed alone and paired. Our results showed that visually paired participants exhibited spontaneous coordination between the movements of their head, hip, and ankle. Moreover, the visual coupling modified the spontaneous intrapersonal ankle-hip coordination dynamics of participants and their performance during visual tracking. Generally, our findings demonstrated reciprocal relations between intrapersonal and interpersonal coordination during social interaction.

Keywords: intrapersonal postural coordination, interpersonal postural coordination, visual coupling

Inspired by the dynamical systems theory in motor behavior (e.g., Kelso, 1995; Kugler & Turvey, 1987), previous research has shown that the coordination between rhythmic movements of two people visually coupled is constrained by the dynamical entrainment processes of coupled oscillators (e.g., Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Schmidt, Carello, & Turvey, 1990). Interpersonal coordination during visual interaction can be characterized by the relative phase angle (ϕ_{rel}) of the two individual rhythmic movements. Among all possible interpersonal coordination, only in-phase ($\phi_{rel} \approx 0°$) and antiphase ($\phi_{rel} \approx 180°$) coordination patterns can be maintained intentionally without practice and the in-phase pattern is more stable than the antiphase pattern (e.g., Schmidt et al., 1998, 1990).

Interestingly, recent studies have also demonstrated that the same dynamics constrains interpersonal coordination when occurring voluntarily and when occurring spontaneously (e.g., Issartel, Marin, & Cadopi, 2007; Oullier, de Guzman, Jantzen, Lagarde, & Kelso, 2008; Schmidt & O'Brien, 1997; Tognoli, Lagarde, de Guzman, & Kelso, 2007). These latter studies have demonstrated that when two individuals are asked to perform rhythmic movements at their own preferred tempo, spontaneous coordination appears when visual information about the movements of the other is available. However, this coordination is intermittent because it is constrained by a weak coupling. In the aforementioned studies, the intermittent coordination is characterized by the occurrence of all possible relative phase values but clustered around 0° and 180°, and with a number of occurrence around 0° greater than around 180° (e.g., Richardson, Marsh, & Schmidt, 2005; Schmidt & O'Brien, 1997).

Even if studies have shown spontaneous interpersonal coordination during visual interaction, questions can still be raised about whether the results can be generalized to interpersonal interactions in the everyday life. Most of these studies have analyzed the movements of single body segments such as the wrist or the index finger involving only 1 df. But single segment movements do not reflect the complexity and variety of interpersonal multi-segment coordination that occurs in our everyday life. Recent investigations have suggested that between-participants in-phase and antiphase coordination can be found in more complex systems involving many degrees of freedom such as the locomotor system (e.g., van Ulzen, Lamoth, Daffertshofer, Semin, & Beek, 2008; Zivotofsky & Hausdorff, 2007) or a "rocking-chair system" (e.g., Richardson et al., 2007). Additionally, interpersonal postural coordination has been studied by Shockley, Santana, and Fowler (2003), a social coordination problem very close to everyday life interactions. In this study, the postural sway of two standing individuals was measured with a movement sensor attached at their waist as they discussed the subtle differences between a pair of similar cartoon pictures that were placed on wooden stands at eye level. Through manipulating the availability of visual and verbal information, the results demonstrated a higher degree of synchronization when participants were interacting verbally, regardless of whether they had visual information about the other person.

In the present study, we evaluated the formation and stability of interpersonal coordination involving the postural system as well. Our interest in this interpersonal situation was motivated by our desire to understand the link between intrapersonal and interpersonal coordination. The properties of intrapersonal and interpersonal coordination have been extensively studied during the recent years, but they have mostly been investigated independently from each other. This is surprising considering that these two coordination dynamics could be closely related in everyday social interac-

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Manuel Varlet, Ludovic Marin, Julien Lagarde, and Benoît G. Bardy, Movement to Health Laboratory, EuroMov, Montpellier-1 University.

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Correspondence concerning this article should be addressed to Ludovic Marin, Movement to Health Laboratory, Montpellier-1 University, EuroMov, 700 Avenue du Pic Saint Loup–34090 Montpellier, France. E-mail: ludovic.marin@univ-montp1.fr

tions. For instance postural movements could be interpersonally spontaneously synchronized with those of another person but at the same time the different body segments of each person have also to be well coordinated to preserve bipedal stance and achieve functional goals (e.g., Riccio, 1993; Riccio & Stoffregen, 1988). Previous studies have shown that multi-segment postural coordination of one person can be described by the relative phase between their hip and ankle in a visual tracking task (e.g., Bardy, Marin, Stoffregen, & Bootsma, 1999). In this latter experiment and follow-up studies, standing participants were instructed to move to maintain a constant distance between their head and a visual target that oscillated along the line of sight. This research revealed that two preferential ankle-hip patterns emerged during visual tracking task: an in-phase mode for low target frequency displacements and an antiphase mode for high target frequency motions, corresponding to ankle-hip relative phases close to 20° and 180°, respectively. Increasing target frequency produced an abrupt change from in-phase to antiphase coordination at a critical target frequency and inversely, decreasing frequency produced a change from antiphase to in-phase coordination (Bardy, Oullier, Bootsma, & Stoffregen, 2002). The dynamics of intrapersonal postural coordination is rooted in the mechanical interactions between the various segments of the body and each person has a unique dynamics that strongly depends on biomechanical properties such as mass, height, or foot length (e.g., Bardy et al., 1999; Bardy, Faugloire, Fourcade, & Stoffregen, 2006; Bonnet et al., 2008; Martin, Cahouët, Ferry, & Fouque, 2006).

Moreover, our additional motivation for the analysis of the different body segments of participants was to examine interpersonal postural coordination during visual interaction with greater measurement precision than that provided by Shockley et al. (2003). Body sway measured at waist level can correspond to many movements of the body segments that preserve bipedal stance because of joints redundancy in the postural system (e.g., Bernstein, 1967; Riccio & Stoffregen, 1988). That is, many flexion and extension combinations of the hips and ankles can generate the same waist movement. As a result, there is no direct correspondence between the degree of interpersonal coordination measured at waist level and the coordination that could be measured more precisely with angular motion of each joint, leaving open the possibility that Shockley et al.'s failure to find evidence for interpersonal postural coordination in response to visual coupling was the result of insufficiently sensitive measurement. Consequently, in the present study, we measured movement of multiple body segments, enabling a more sensitive and detailed analysis of interpersonal postural coordination.

Thus, the extent to which visual interaction with another person can produce interpersonal postural coordination and modify someone's intrapersonal postural coordination remains unclear. In the present study, we used a postural (i.e., multi-joint) coordination paradigm adapted from the tracking task used by Bardy et al. (2002) to test whether visual coupling is sufficient for interpersonal postural coordination to occur spontaneously, and how interpersonal coordination would affect intrapersonal postural coordination. Considering the necessity of controlling intrapersonal coordination to maintain balance, the strength of visual coupling with another person could be insufficient to produce spontaneous interpersonal coordination; on the other hand, given evidence elsewhere for spontaneous interpersonal synchronization in response to visual coupling (e.g., Issartel et al., 2007; Oullier et al., 2008; Richardson et al., 2007), the drive/tendency to synchronize with others might be sufficient to induce interpersonal postural coordination, with implications for intrapersonal personal coordination. Our general hypothesis was that if visual coupling is sufficient to prompt synchronization, then spontaneous interpersonal postural coordination toward in-phase and antiphase patterns and resultant modifications of intrapersonal postural coordination dynamics would emerge when participants performed a visually coupled interpersonal visual tracking task.

Method

Participants

Twenty adults volunteered to participate in the experiment. All reported normal or corrected-to-normal vision and none were informed about the aims of the study. The age of participants ranged from 19 to 28 years old ($M = 23.30$, $SD = 2.85$). Their mean height was 171.60 cm ($SD = 9.89$) and their mean weight was 63.85 kg ($SD = 8.59$). Five female pairs and five male pairs were randomly created, independently of their biomechanical properties. The mean of within-pair height difference was 6.80 cm ($SD = 6.46$) and the mean of within-pair mass difference was 7.10 kg ($SD = 5.53$).

Task and Procedure

Participants stood barefoot on the laboratory floor and had to perform a visual tracking task similar to the one used by Bardy et al. (2002). They were instructed to track with their head movements the oscillations of the target in the antero-posterior axis, matching the amplitude and phase of their head movement with the amplitude and phase of the target motion. The target was simulated on a computer screen by a green square on a black background. The screen measured 0.48 m in diagonal and was positioned 2.25 m from the participant at eye level. Expansion and contraction of the square simulated the target oscillations with a constant peak-to-peak amplitude of 0.10 m. Four series were presented in a counterbalanced order, two with a progressive increase in target frequency from 0.10 Hz to 0.75 Hz, and two with a progressive decrease from 0.75 Hz to 0.10 Hz. Each series was composed of fourteen frequency segments of ten target oscillation cycles (i.e., 140 cycles for each series). The total duration of a series was 7.44 min. A 5-min break was given between the series.

This visual tracking task was performed in two counterbalanced conditions. The two participants of the pair performed the task simultaneously in the Duo condition (i.e., Figure 1A) and alone in the Solo condition (i.e., Figure 1B). In the Duo condition, participants were positioned sideways to each other to have the target in central vision and the other participant at a distance of 2.15 m in peripheral vision at 21.8° left of center. Because the visual tracking task was the focal task and the visual tracking target and the other participant could not both be placed in central vision, the tracking task target was placed in the privileged central position even if the peripheral view of the other participant could decrease interpersonal coordination (Richardson et al., 2007). The target was represented simultaneously on two identical screens with similar displacements (i.e., expansion and contraction without time-lag

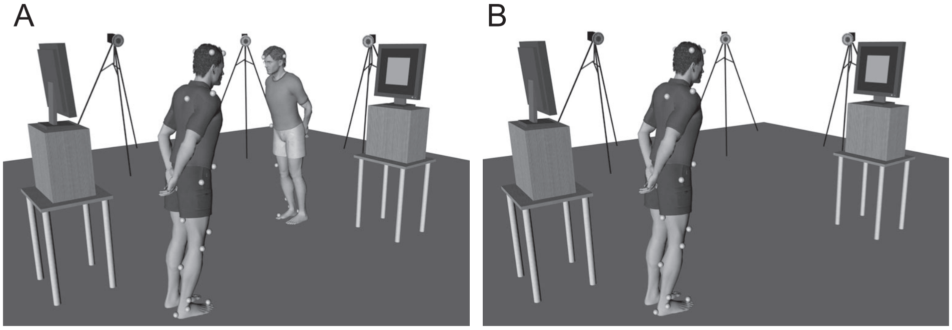


Figure 1. Experimental setup. (A) Duo condition: Participants of each pair performed the visual tracking task together. (B) Solo condition: Trials were performed alone by each participant of the pair. Only the presence or absence of the other participant differentiated the two conditions.

between the displays). In the Duo condition, no instruction was given about the behavior to adopt with the other participant. In the Solo condition, each participant of the pair performed the task separately. Their data were paired post hoc, which was possible because body motion and visual target displacements were synchronized. Thus, the Solo condition allowed us to determine the intrapersonal ankle-hip coordination of each participant and the baseline of interpersonal coordination obviously imposed by target synchronization that could be used in comparison to the Duo condition.

Data Acquisition and Dependent Variables

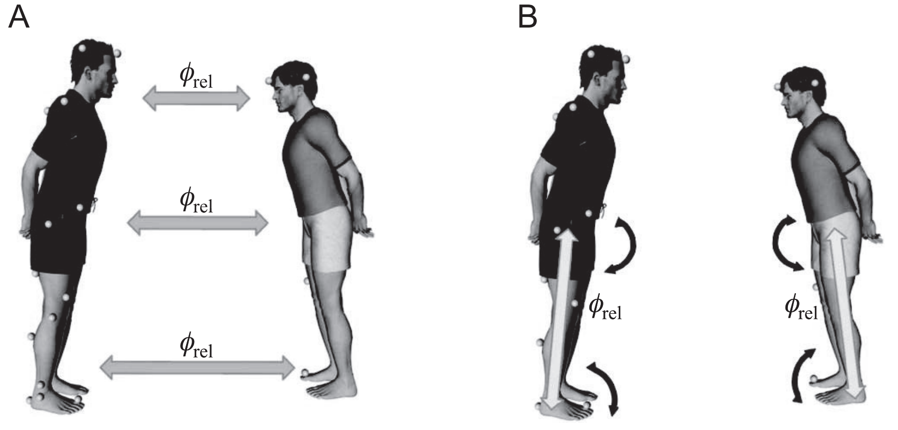
The movements of each participant were collected at a sampling rate of 100 Hz by using fifteen reflecting markers placed on their right side and captured by eight infrared MX13 cameras (Vicon-Nexus, Oxford Metrics Ltd.). Markers located on the side of the head, shoulder (acromion), hip (greater trochanter), knee (estimated knee joint center), ankle (lateral malleous), and toe (head of the fifth metatarsal) were used to capture the front-to-back head displacements of participants and the angular motions of their hip and ankle. To analyze the spontaneous interpersonal postural coordination, the intrapersonal ankle-hip coordination of the participants and their visual tracking performance, nine variables were computed for each frequency segment in the Duo and Solo conditions. Each variable was computed on the last nine cycles of each frequency segment to avoid transient behavior caused by the change in the target frequency.

Tracking task performance. Three variables were computed to determine the performance of participants in the visual tracking task: (1) the mean head-target gain corresponding to the ratio of (the amplitude of) the head displacements and the target displacement; (2) the relative phase between oscillations of the target and oscillations of the head in the antero-posterior direction; and (3) the standard deviation of the head-target relative phase. The laboratory frame was chosen as a reference to compute head-target relative phase following previous research (Bardy et al., 1999, 2002). Perfect performance in the visual tracking task would be defined by a gain equal to 1 and a value of relative phase and its standard deviation equal to 0.

Interpersonal postural coordination. The relative phase between movements of the head, hip, and ankle of each pair of participants were computed to analyze spontaneous interpersonal postural coordination (i.e., Figure 2A). The laboratory frame here was *not* chosen to compute relative phase values; the in-phase pattern corresponded to a simultaneous flexion or extension of the participants' joints. In other words, when the participants were positioned side way to each other and performed the same movements to track the target, movements of their head, hip and ankle were in-phase. Because spontaneous interpersonal coordination during visual interaction appears intermittently and was consequently nonstationary, the standard deviation of the relative phase is not appropriate for measuring the stability of these coordination. Thus, we have analyzed the distribution of relative phase to compare head-head, hip-hip, and ankle-ankle interpersonal coordination in Duo and Solo conditions (e.g., Richardson et al., 2007, 2005; Schmidt & O'Brien, 1997). In line with the literature, each of these distributions contained nine 20° regions of relative phase between 0° and 180° and a percentage of occurrence of relative phase in each of these regions was calculated. A higher percentage of occurrence around 0° and/or 180° was expected for these distributions if visual coupling was sufficient to produce spontaneous interpersonal coordination toward in-phase and/or antiphase patterns.

Intrapersonal postural coordination. Three variables have been computed from ankle-hip relative phase values of each participant to investigate the influence of visual coupling on the spontaneous intrapersonal postural coordination dynamics (i.e., Figure 2B): (1) the distribution and (2) the standard deviation of ankle-hip relative phase (characterizing intrapersonal ankle-hip patterns and their stability) as well as (3) the absolute difference between the postural transition frequency of each participant of the pair. This latter variable determined the influence of visual coupling on their postural pattern change. As for head-target relative phase, the laboratory frame was chosen to compute ankle-hip relative phase in accordance with previous research (Bardy et al., 1999, 2002). The in-phase pattern corresponded to a simultaneous flexion (or extension) of the ankles and the hips.

We now describe the method employed to determine the transition frequency (TF) of each participant. The TF corresponded to the critical target frequency for which participants changed from in-phase pattern to antiphase pattern for increasing series and from antiphase pattern to in-phase pattern for decreasing series. In other



Interpersonal Postural Coordination Intrapersonal Postural Coordination

Figure 2. Relative phase analyzed to investigate interpersonal and intrapersonal postural coordination. (A) Head-head, hip-hip, and ankle-ankle relative phases were computed to analyze interpersonal postural coordination. (B) Ankle-hip relative phase of each participant was computed to analyze intrapersonal postural coordination.

words, the TF was the frequency for which the last relative phase value was in its original interval before entering the new mode. To compute the TF we have defined intervals over which in-phase and antiphase patterns were considered as stable for both increasing and decreasing series. For in-phase the interval was [$\phi\mu1 - SD(\phi\mu1)$, $\phi\mu1 + SD(\phi\mu1)$], where $\phi\mu1$ and $SD(\phi\mu1)$ were, respectively, the mean and standard deviation of ankle-hip relative phase computed at 0.10 Hz (i.e., Figure 3). For antiphase this interval was [$\phi\mu2 - 2 \times SD(\phi\mu2)$, $\phi\mu2 + 2 \times SD(\phi\mu2)$], where $\phi\mu2$ and $SD(\phi\mu2)$ were respectively the mean and standard deviation of ankle-hip relative phase computed at 0.75 Hz. We have tested different sizes of interval on our data and have kept these because they permitted to determine transition frequencies of all participants with the highest precision. To compute the mean and standard deviation of the intervals, corresponding values to the first and last cycle were not kept because they corresponded to the initial change in target frequency.

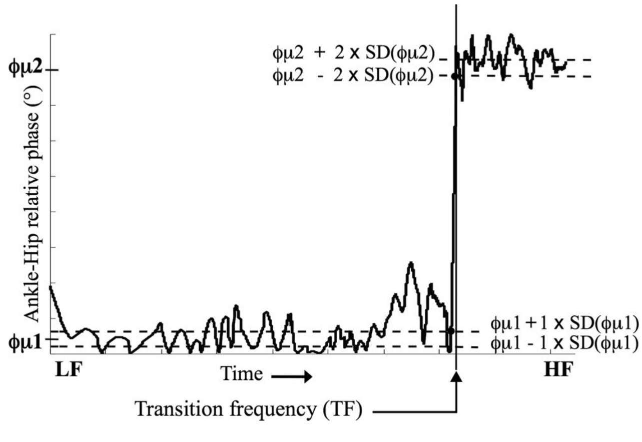


Figure 3. Method for determining the transition frequency (TF). $\phi\mu$: mean of relative phase; SD($\phi\mu$): standard deviation of relative phase; LF: low frequency and HF: high frequency.

Relative Phase Computation

A Cross Wavelet Transform (CWT) method was used to compute all relative phase values. CWT is a time-frequency analysis that provides information about frequency synchronization between two signals and the continuous relative phase between them corresponding to the common frequency. The advantages of this method over classical methods were recently demonstrated in the analysis of human interpersonal relative phase (Issartel, Marin, Bardainne, Gaillot, & Cadopi, 2006; Issartel et al., 2007).

All CWT were performed with the complex Morlet function of order 8 and a band of frequency ranging from 0.05 Hz to 3 Hz. A significant level of 0.05 was used for the statistical test of Torrence and Compo (1998) associated with the CWT that enabled to identify the significant common frequencies. At each time point, for the frequency corresponding to the highest level of frequency locking, the continuous relative phase between 0° and 180° was extracted. When there was no significant common frequency, no value of relative phase was extracted. If more than one half of a given segment could not be extracted, this segment was not kept for further analysis.

Results

The goal of the current study was to determine whether visual coupling was sufficient to produce spontaneous interpersonal coordination between the movements of two individuals, and to influence their spontaneous intrapersonal postural coordination during a visual tracking task. The results were computed with 80 trials in total (i.e., 40 for Duo condition and 40 for Solo condition) of ten experimental pairs. The number of frequency segments for which no relative phase could be extracted was: 0/1120 for head-head relative phase; 0/1120 for hip-hip relative phase; 37/1120 for ankle-ankle relative phase; 1/2240 for ankle-hip relative phase; and 0/2240 for head-target relative phase.

Tracking Task Performance

The mean of head-target gain, head-target relative phase and head-target relative phase standard deviation were respectively 1.77 (*SD* = 0.50), 28.42° (*SD* = 12.10), 6.49° (*SD* = 1.57) for the Duo condition and 1.71 (*SD* = 0.55), 27.10° (*SD* = 9.83), 5.77° (*SD* = 1.48) for the Solo condition. Although head displacements were of higher amplitude than target displacements, and with a small time lag, the instructions of the task were reasonably well respected in Duo and Solo conditions. Repeated-measures ANOVA did not reveal significant difference between Duo and Solo conditions for the head-target gain and the mean of head-target relative phase, indicating that these variables were not affected when participants were visually coupled ($F(1, 19) = 1.35$, $p > .05$, $\eta^2 = 0.07$); $F(1, 19) = 0.20$, $p > .05$, $\eta^2 = 0.01$). However, a significant difference was revealed between Duo and Solo condition for head-target relative phase standard deviation ($F(1, 19) = 6.75$, $p < .05$, $\eta^2 = 0.26$). The tracking variability increased when participants were visually coupled.

Interpersonal Postural Coordination

The distributions of relative phase values between the head, hip, and ankle movements of participants in Duo and Solo conditions were compared to determine whether visual coupling was sufficient to produce spontaneous interpersonal postural coordination during the visual tracking task.

Distribution of head-head relative phase. Generally, the distributions of relative phase between the front-to-back head displacements of participants showed a high percentage of occurrence around 0° in Duo and Solo conditions because the motions of the targets were programmed to be rigidly synchronized on in-phase pattern (i.e., Figure 4A). However, the statistical analysis revealed a higher percentage of occurrence around 0° in Duo condition. The distribution of head-head relative phase across the nine phase regions was submitted to a 2 (Conditions) × 9 (Phase Region) repeated-measures ANOVA. Using a Greenhouse-Geisser correction, this analysis yielded a significant main effect of phase region ($F(8, 72) = 70.45$, $p < .05$, $\eta^2 = 0.89$) and a significant interaction between phase region and conditions ($F(8, 72) = 12.39$, $p < .05$, $\eta^2 = 0.58$). A post hoc comparison (Newman-Keuls test) showed that the percentage of occurrence for phase region 0 to 20° was significantly higher in the Duo condition than in the Solo Condition ($p < .05$), and that the percentage of occurrence for the region 20 to 40° was significantly lower in the Duo condition than in the Solo condition ($p < .05$). Although target synchronization produced a baseline head-head in phase pattern in the two conditions, this coordination pattern was reinforced when participant were visually interacting. To summarize, the analysis of front-to-back head displacements of participants showed that although they were only instructed to do their best to track the motion of the target, the visual information available about the other person produced a decrease in head-target coordination and a spontaneous increase in interpersonal head-head coordination.

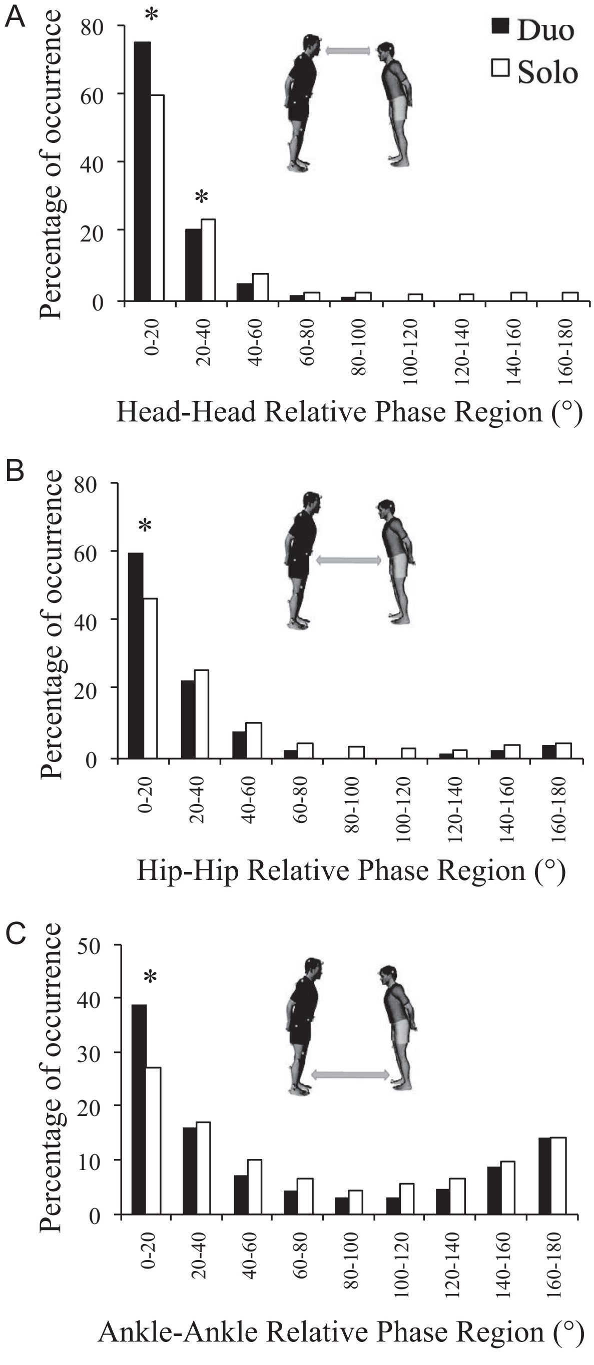


Figure 4. Distribution of head-head (A), hip-hip (B), and ankle-ankle (C) relative phase values for Duo (black) and Solo (white) conditions.

Distribution of hip-hip relative phase. As for head movements, the distribution of hip-hip relative phase exhibited a higher percentage of occurrence around 0° in the two conditions because of target synchronization. Here again, this coordination was greater in the Duo condition (i.e., Figure 4B). The distribution of hip-hip relative phase across the nine phase regions was submitted to a 2 (Conditions) × 9 (Phase Region) repeated-measures ANOVA. Using a Greenhouse-Geisser correction, this analysis yielded a significant main effect of phase region ($F(8, 72) = 29.57$, $p < .05$, $\eta^2 = 0.77$) and a significant interaction between phase region and conditions ($F(8, 72) = 7.19$, $p < .05$, $\eta^2 = 0.44$). A post hoc comparison (Newman-Keuls test) showed that the percentage of occurrence for phase region 0 to 20° in Duo condition was significantly higher than the one obtained in Solo Condition ($p < .05$). This result showed that the hip movements of participants were spontaneously synchronized toward in-phase pattern during visual interaction.

Distribution of ankle-ankle relative phase. Contrary to head and hip movements, a high percentage of occurrence was both observed around 0° and 180° for ankle-ankle relative phase distribution in Duo and Solo conditions (i.e., Figure 4C). The two postural patterns adopted preferentially by participants to track the target explained this result. Ankle movements of the two participants were in-phase when they adopted similar preferential postural patterns and, contrary to head and hip movements, they were in antiphase when they adopted different postural patterns. However, a higher percentage of occurrence was also observed around 0° in the Duo condition. The distribution of ankle-ankle relative phase across the nine phase regions was submitted to a 2 (Conditions) × 9 (Phase Region) repeated-measures ANOVA. Using a Greenhouse-Geisser correction, this analysis yielded a significant main effect of phase region ($F(8, 72) = 9.27$, $p < .05$, $\eta^2 = 0.51$) and a significant interaction between phase region and conditions ($F(8, 72) = 5.35$, $p < .05$, $\eta^2 = 0.37$). A post hoc comparison (Newman-Keuls test) showed that the percentage of occurrence for the 0 to 20° phase region in the Duo condition was significantly higher than the one obtained in the Solo Condition ($p < .05$), demonstrating the presence of spontaneous ankle-ankle in-phase interpersonal coordination when participants were paired.

To summarize, despite an important degree of in-phase coordination between participants because of the target synchronization, the in-phase pattern was observed more often when participants were visually coupled. These findings showed that visual information was sufficient to produce spontaneous interpersonal coordination between head, hip, and ankle movements during the visual tracking task. However, no increase in the percentage of occurrence around 180° was observed in the Duo condition, indicating that spontaneous coordination was clustered only around in-phase for these three kinds of coordination.

Intrapersonal Postural Coordination

Three variables were computed from the ankle-hip relative phase values of each participant to investigate their intrapersonal postural coordination dynamics during the visual tracking task in Solo and Duo conditions.

Distribution of ankle-hip relative phase. Generally, a high percentage of occurrence around 20° and 180° was observed both in Duo and Solo conditions, corresponding to the two preferential postural patterns observed in previous studies (i.e. Figure 5). The relative phase distribution was about the same in Solo and Duo conditions. The distribution of ankle-hip relative phase across the nine phase regions was submitted to a 2 (Conditions) × 9 (Phase Region) repeated-measures ANOVA. Using the Greenhouse-Geisser correction this analysis yielded a significant main effect for phase region ($F(8, 152) = 63.26$, $p < .05$, $\eta^2 = 0.77$) and no significant interaction between phase region and conditions ($F(8, 152) = 0.20$, $p > .05$, $\eta^2 = 0.01$). Quantitatively, participants did not produce different in-phase or antiphase patterns when they were visually coupled.

Standard deviation of ankle-hip relative phase. The standard deviation of ankle-hip relative phase was 8.24 ($SD = 4.36$) in the Duo condition and 8.56 ($SD = 5.44$) in the Solo condition. No difference in the variability of the ankle-hip relative phase was found between the two coordination conditions ($F(1, 19) = 0.14$, $p > .05$, $\eta^2 = 0.01$).

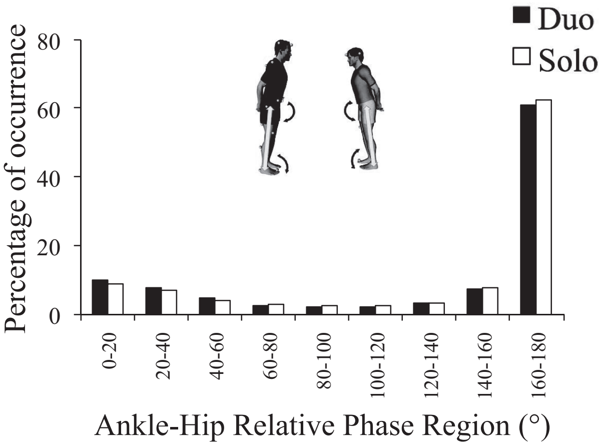


Figure 5. The distribution of ankle-hip relative phase for Duo (black) and Solo (white) conditions.

Absolute difference between postural transition frequencies. The absolute difference between the transition frequencies of each participant of the pair was computed to determine whether the visual coupling influenced their postural transition during the tracking task. Within the 80 ankle-hip relative phases extracted from the CWT, 15 (i.e., 9 for Duo condition and 6 for Solo condition) were not analyzed because they did not contain one or two stable patterns within the trial. Consequently, one of our 10 experimental pairs was eliminated for the computation of the absolute difference between postural transition frequencies. Moreover, we observed some trials (i.e., 28 %) in which no transition between patterns occurred when frequency was increased or decreased. In these trials, participants maintained an antiphase pattern throughout the trial. We have arbitrary attributed a transition frequency of 0 Hz to these trials. Although this procedure did not allow us to compute the mean transition frequency in Duo and Solo conditions (not reported here), it allowed us to determine without bias the absolute difference between postural transition frequencies. This procedure further allowed us to capture the relative influence in the dyad of a participant who did not bifurcate on a participant who did and vice versa.

The mean absolute difference between the transition frequencies of the nine remaining pairs was 0.21 Hz ($SD = 0.15$) for the Duo condition and 0.27 Hz ($SD = 0.15$) for the Solo condition. A 1-factor ANOVA with repeated measures showed a significant difference between the two conditions ($F(1, 8) = 20.25$, $p < .05$, $\eta^2 = 0.72$) (i.e., Figure 6A). The results indicated that participants had the tendency to match their transition frequencies in the Duo condition (e.g., Figure 6B). They anticipated or delayed their transition from one pattern to the other to remain posturally coordinated with the other participant.

Discussion

The current experiment investigated whether visual coupling between two people involved in the same task could influence their

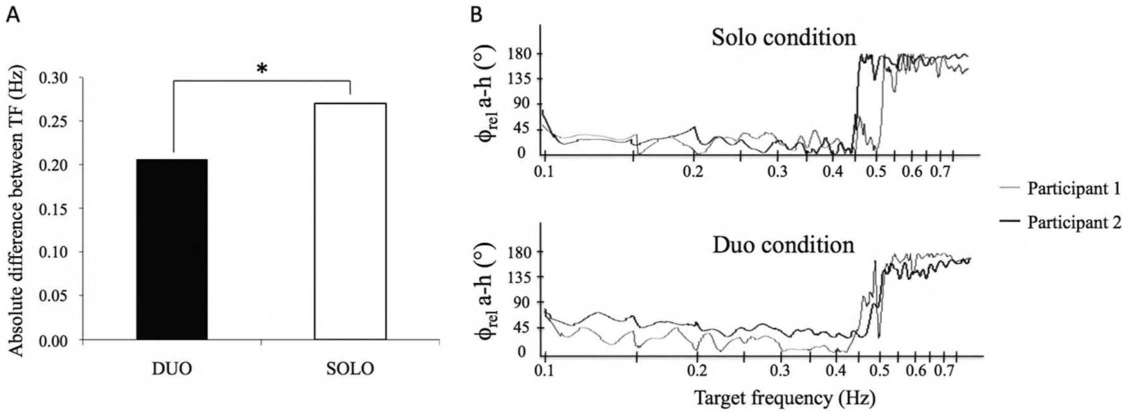


Figure 6. (A) Absolute difference between transition frequency (TF) in Duo and Solo conditions. (B) Ankle-hip relative phase of two representative participants in Duo and Solo conditions illustrating the tendency of participants to match their postural transition frequency when paired.

intrapersonal ankle-hip coordination and produce spontaneous interpersonal postural coordination. To answer this question, we analyzed the phase synchronization between the head, hip and ankle movements of participants, as well as their spontaneous intrapersonal ankle-hip coordination during a visual tracking task performed alone and paired. Our results indicated that visual information available about the other person produced spontaneous interpersonal postural coordination between our participants and influenced their head-target and intrapersonal ankle-hip coordination. We now discuss these findings and propose a simple model to account for them.

Interpersonal Postural Coordination

The relative phasing between head, hip, and ankle movements were analyzed to investigate the interpersonal postural coordination during visual tracking. If visual information was sufficient to produce spontaneous coordination, we predicted an increase in relative phase occurrence around 0° and 180° comparative to other relative phase regions. An increase in relative phase occurrence around 0° was observed for head, hip, and ankle movements when participants were paired. Despite the fact that they were only instructed to maintain a constant distance between their head and the target, when visual information about the other participant was available in peripheral vision, their movements were spontaneously attracted towards an in-phase interpersonal relation. Such an "attraction" did not occur for the antiphase relation. The in-phase interpersonal relation was obviously privileged by the synchronization of the targets tracked. With similar target displacements for each participant of the experimental pair, an antiphase coordination of head displacements would have been incompatible with the respect to the instructions. In addition, spontaneous coordination toward antiphase pattern is known to disappear when the visual coupling between participants is too weak, a result already found for spontaneous visual synchronization of index finger movements (e.g., Oullier et al., 2008), forearm movements (e.g., Issartel et al., 2007) and rocking chair movements (e.g., Richardson et al., 2007). In our experiment, the weak strength of the visual coupling could be explained by the peripheral nature of the visual information available about the other participant. In fact, Richardson et al. (2007) have shown a significant difference between peripheral and focal visual information on the degree of spontaneous interpersonal coordination. It may well be the case that the strength of visual coupling in our experiment could have been increased if participants were facing each other more focally, a hypothesis that we consider as an important research direction.

Thus, the spontaneous coordination that we found between the two postural systems during visual interaction extends previous results obtained with other simpler interpersonal coordination involving less and/or different degrees of freedom (e.g., Richardson et al., 2007; Schmidt & O'Brien, 1997; van Ulzen et al., 2008). However, our findings were not in accordance with Shockley et al.'s (2003) results. The authors did not find any spontaneous coordination between two standing individuals visually coupled. What can account for this difference? Shockley et al. have not analyzed the angular displacements of the hip and ankle, and it is possible that such an analysis would have revealed spontaneous coordination. In addition, the constraints imposed on body sway by the two tasks certainly explain the difference. Contrary to Shockley et al. (2003), body sway in our study was rhythmic and constrained by the periodic movement of the target. Moreover, our visual tracking task imposed an amplitude of body sway of (17 cm) about four times larger than the natural body sway amplitude observed in their quiet stance experiment (around 4 cm, cf. Bensel & Dzendolet, 1968), encouraging functional synergies between body segments. We now discuss whether the interpersonal coordination that appeared spontaneously when participants were paired influenced their head-target coordination dynamics.

Decrease of Performance in Tracking Task

The analysis of front-to-back head displacements revealed changes in head-target coordination variability when participants were paired. Head-target absolute gain and phase values were not affected but the standard deviation of relative phase increased in the Duo condition compared to the Solo condition. Here we believe there was a mutual influence of both head-target coupling and partner-to-partner coupling.

Partner vs. target coupling competition. We found that the availability of a visual coupling between individuals increased synchrony between the two heads, while it actually decreased synchrony between individual head and target. When compared to the Solo condition, one may expect that the visual coupling between participants available in the Duo condition would strengthen, or at least would not affect, the synchronization between any pair of components within the whole system (e.g., head-head, head-target). This intriguing result may be produced by a competition between two coupling functions: the *coupling-to-partner* function and the *coupling-to-target* function. In order for such competition to exist, one needs nonequivalent visual information available from the motion of the target and from the motion of the partner, or a degree of discrepancy between movements of the two participants.

We envision three intuitive scenarios that could bring in a target-partner competition. First, one may seek asymmetries between the individuals' perception-action dynamics, considering a simple model focusing on head motion, which is outlined below. Second, direct kinematics for the tracking task using a double inverted pendulum model (e.g., Bonnet al., 2008) indicates how some discrepancies between participants movement may appear. In the double inverted pendulum scenario, differences in body sizes can introduce asymmetries between hip and ankle joint amplitudes and velocities among partners, while both heads can be equivalently frequency and phase locked to the target, with identical amplitudes. Again, reasoning with a simple direct kinematic model of the task, assuming that the head is moving only horizontally, a redundancy between head and joint movements exists, which would enable identical head displacements produced by quantitatively different relative phasing between ankles and hips (e.g., Bonnet al., 2008, 2009). Finally one may argue that vision of the partner in the Duo condition introduces in the visual field a discrepancy between a fully regular sinusoidal motion of the target and a motion of the partner displaying stochastic fluctuations, which is a ubiquitous property of biological movement (Schöner, Haken, & Kelso, 1986).

The simulations presented below involve a fully sinusoidal target with stochastic dynamics for the head, to account for the presence of noise. We focus on the first candidate scenario (with the addition of noise) to determine whether a simple model can reproduce qualitatively this rather counterintuitive partner and target competition. We are aware that a double-inverted pendulum analogy may also be interesting in the long-run to fully account for interpersonal postural coordination dynamics because a double-inverted pendulum can capture the coordination patterns characterizing the postural system. The model we use does not incorporate the neurophysiological or biomechanical underpinnings of postural dynamics or control. This does not mean that these underpinnings are not important (e.g., Beek, Peper, & Stegeman, 1995). However, this model captures the relationships between postural control and perceptual information.

A simple model. Here we present a model accounting for the competition between the coupling to the target and the coupling to the partner. The model is composed of two moving heads, each being coupled unidirectionally to a target, and of a mutual coupling between the heads to simulate the Duo situation. From related experimental and modeling studies of the postural system in the field of perception-action dynamics (Schöner, 1991), we retained the following assumptions: The state of the postural system is described by the position, x, of the eye in the laboratory frame. The direction of displacement of the eye can be considered as normal to the screen on which the target is displayed. In the present study, the task required the subject to actively generate its own motion to track the periodically moving target; hence, we considered that the eye is behaving as a self-sustained oscillator. These assumptions aimed at simplifying the model, and are in agreement with an emphasis on functional, low dimensional, perception-action coordination dynamics (Kelso, 1995; Warren, 2006).

In Equation (1) below, the left-hand side function accounted for the so-called intrinsic dynamics of the components (Haken, Kelso, & Bunz, 1985; Kay, Kelso, Saltzman, & Schöner, 1987), and provided a limit-cycle behavior reproducing the single effectors dynamics. The right-hand side function accounted for the coupling between the components. The Haken, Kelso, Bunz (HKB) coupling provided the multistable dynamics characterizing bimanual and interpersonal coordination using 1 df components (e.g., Schmidt et al., 1990; Tognoli et al., 2007). Following Kelso, DelColle, and Schöner (1990) and Schöner and Kelso (1988) we included a forcing function representing the unidirectional coupling between the effectors and the external stimuli. Under these assumptions, the model we simulated numerically is governed by a dynamical system of the form:

$$\ddot{x} + (Ax^2 + B\dot{x}^2 - \gamma)\dot{x} + \omega_1^2 x = K1(\alpha + \beta(x - y)^2)(\dot{x} - \dot{y}) + F\cos\Omega t + \xi(t) \quad (1)$$

$$\ddot{x} + (Ax^2 + B\dot{x}^2 - \gamma)\dot{x} + \omega_2^2 x = K2(\alpha + \beta(x - y)^2)(\dot{x} - \dot{y}) + F\cos\Omega t + \xi(t)$$

Where $K_{1,2}$ represent the strengths of the HKB bimanual (interpersonal) coupling function, $\omega_{1,2}$ are the eigenfrequencies of the oscillators (i.e., two postural systems), F is the strength of the forcing function that represented the environmental information, here specified by a moving target. Additive white noise, $\xi(t)$, with zero mean, unit variance, and delta correlated, accounted for the occurrence of fluctuating postural sway, following the stochastic framework applied to coordination dynamics by Schöner et al. (1986).

To assess our assumptions about the origin of the competition from asymmetries between partner dynamics and couplings, we combined in our main simulation the effect of unequal eigenfrequencies among partners ($\omega_{1,2} = 2.0$ Hz and 2.3 Hz, respectively) and unequal strengths for reciprocal couplings ($K_{1,2}$). The symmetry between reciprocal couplings of the heads was varied by increasing the coupling strength *K1* from 0 to 1.5 in 50 linearly spaced steps, while keeping the coupling *K2* equal to 0.2. The frequency of the forcing target was varied from 0.3 to 0.4 with 30 linearly spaced steps. We assessed the effect of these parameters changes on the dispersion of the relative phases between heads and between each head and the target. For comparison, we performed three complementary simulations of the same basic model: (1) with fully symmetric components and coupling terms, (2) with unequal eigenfrequencies among partners associated with equal couplings, and (3) with equal eigenfrequencies among partners associated with unequal couplings. Finally, in a fourth control simulation we aimed at implementing the impact of "attentional sharing" between the target and the partner. We considered that in the Solo condition 100% of the attention is devoted to the target, and that in the Duo condition the attention is split between the target and the partner. Hence, for this fourth simulation, we tested a model with unequal eigenfrequencies associated with equal reciprocal couplings between the heads; the coefficients of the reciprocal couplings were increased linearly like in the other simulations (K in Equation 1). The novelty in this fourth simulation was the decrease of the strength of the forcing function (F in Equation 1), inversely proportional to the coefficient of the reciprocal couplings between the heads ($F = 1/K$).

The numerical integration used an Euler-Maruyama scheme for stochastic differential equations to perform 50 simulations for each level of parameters, a path length of 15,000 points for each realization, with a time step of 0.01, and noise strength of 0.1. A measure of synchronization representing the stability of locking, the dispersion of relative phase, was calculated from the outputs of the simulations, and then averaged across simulations. To improve accuracy, we reduced the periodic variability arising from the specific coordinates used to extract the instantaneous phase of each oscillator (Fuchs, Jirsa, Haken, & Kelso, 1996) using the method proposed in Kralemann et al. (2007).

We found that combining asymmetric eigenfrequencies and coupling strengths was the only configuration providing at the same time for a range of frequency (1) a reduction of synchronization between the head and the target for one of the two participants, and (2) an increase in coordination between the heads, with an increase in coupling strength (i.e., Figure 7). The outputs of the other four simulations failed to show any competition between the coupling to the target and the coupling to the partner.

Hence, a competition between target forcing and partner coupling decreasing the stability of the coordination can originate from asymmetries even in a very simplified model. No efforts were made to specifically fit the parameters to the data to reproduce quantitatively the results of the experiment, as we aimed at a qualitative answer for the potential origin of the competition between partner and target. Following stringent assumptions we obtained a subtle effect, restricted to one oscillator in a pair. Taking these limitations into account, this numerical investigation shows that the seemingly counter intuitive effect obtained can indeed be accounted for by a simple model, which motivates further explorations. Importantly, using the same basic assumptions, we showed that several parameterizations of the same model are not able to reproduce the competition effect, in particular when only one of the two sources of asymmetry was present, either unequal eigenfrequencies or unequal reciprocal couplings.

Modifications of Intrapersonal Postural Coordination Dynamics

Overall, the relative phase values and the stability of the intrapersonal ankle-hip coordination were not significantly affected in the Duo condition compared to the Solo condition. However, a decrease in the absolute difference between the postural transition frequencies of each participant of the pair was observed during visual interaction. This result showed that a visual coupling is sufficient to influence spontaneous intrapersonal postural coordination dynamics. These findings are related to classic research on visual coupling with the environment during stance (e.g., Dijkstra, Schöner, & Gielen, 1994; Lee & Lishman, 1975; Stoffregen, 1985) but extend them in situations where the "environment" includes other humans. Even if the visual coupling involved in interpersonal coordination is known to be weaker than the coupling involved in intrapersonal coordination (Richardson, Lopresti-Goodman, Macini, Kay, & Schmidt, 2008; Schmidt et al., 1998), postural dynamics in social context seem to depend conjointly on ankle-hip

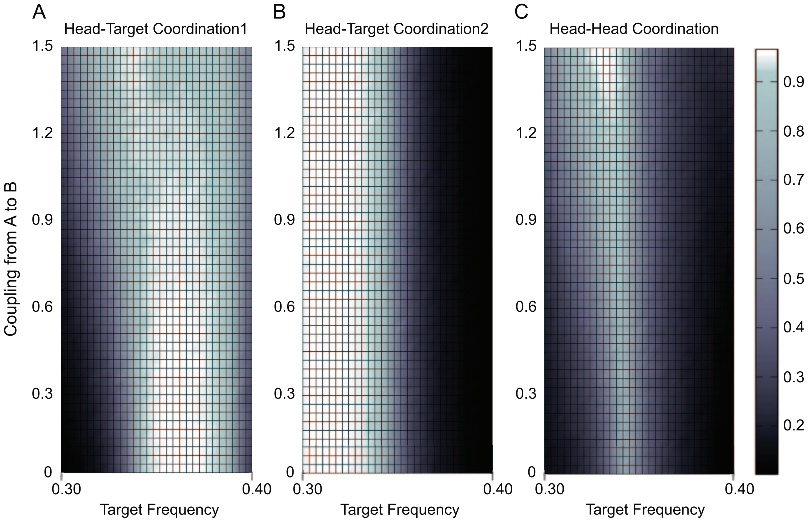


Figure 7. Simulated outputs of equation 1. The synchronization index averaged across simulations bounded in the interval [0 1], 1 corresponding to perfect phase synchronization, is shown for the 50 equally spaced levels of coupling strength from oscillator 2 to oscillator 1, K_1 in Equation (1) (corresponding to increased value from 0 to 1.5), while coupling strength from 1 to 2 (K_2 in Equation 1) is kept constant (0.2), and for the 30 values of the target's frequency (value ranging from 0.3 to 0.4). (A) Coordination to the target for oscillator 1. (B) Coordination to the target for oscillator 2. (C) Coordination between the oscillators 1 and 2.

intrinsic coupling and the visual coupling that linked body movements of the pair. In others words, the behavior adopted by participants to track the target resulted from equilibrium between *within* (spontaneous ankle-hip) postural coordination and *between* (interpersonal) postural coordination. Specifically, participants shifted intrapersonal postural coordination patterns either earlier or later than when alone, to be in-phase with the movements of the co-actor. The transitions occurring later demonstrated that visual coupling could stabilize the intrapersonal ankle-hip coordination and delay the transition.

This result is in accordance with previous research showing a stabilization of intrapersonal coordination by external visual information: Zanone and Kelso (1992) have shown that specific bimanual coordination can be stabilized by using visual metronome composed with two LED specifying the relative phase. However, the visual specification of the relative phase in our experiment comes from a biological system and may have more relevance for participants than the one coming from a nonbiological system such as a visual metronome. Our movements are indeed known to be more influenced by the observation of biological motion (e.g., movement of a human) than by the observation of nonbiological motion (e.g., movement of a robot) (Kilner, Paulignan, & Blakemore, 2003). Whether intrapersonal coordination can be better stabilized when the relative phase is visually specified by the movement of another person or by a nonbiological system remains an open question.

In conclusion, this study has demonstrated that visual interaction between two people is sufficient to spontaneously produce interpersonal postural coordination and influence their intrapersonal postural coordination. Intrapersonal and interpersonal postural coordination dynamics coexist during usual social interactions and we have demonstrated the validity of the postural coordination paradigm to investigate their relationship. Investigating the relationship of intrapersonal and interpersonal coordination will improve our comprehension of the social human motor behavior in general and in understanding its role in social deficits (Mittal & Walker, 2007) and motor learning (Faugloire, Bardy, & Stoffregen, 2006) or rehabilitation (Seigle, Ramdani, & Bernard, 2009) in particular.

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