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Individual contributions to (re-)stabilizing interpersonal movement coordination

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HIGHLIGHTS

- While two persons coordinated their rhythmic arm movements one of the arms was briefly perturbed.
- Both participants adapted their movements to re-establish the shared coordination pattern.
- Interpersonal coordinative stability resulted from symmetrical bidirectional coupling.
- The symmetry in coupling strength was not affected by the coordination pattern performed.
- The applied methodology can be used to examine sources of asymmetry in interpersonal interactions.

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ABSTRACT

Interpersonal movement coordination is characterized by stable coordination patterns. We examined the extent to which the two individuals within a dyad contributed to the stabilization of a shared coordination pattern. Within each dyad, the two participants coordinated rhythmic movements of their right lower arms in either in-phase or antiphase. We analyzed the responses to precisely controlled mechanical perturbations to one of the arms that disrupted the coordination pattern. Return to the original coordination pattern did not only involve phase adaptations in the perturbed arm, but in the unperturbed arm as well. Hence, the coupling between the companions was bidirectional and subserved the coordinative stability. Moreover, for both coordination patterns the interpersonal coupling was near symmetrical, with both actors (perturbed and unperturbed) contributing to the same extents to the restabilization of the coordination between them. The applied methodology provides a new entry point to examine asymmetries in interpersonal coupling, due to, for instance, social impairments, differences in social competence, or particular task setting.

1. Introduction

When interacting with one another, people tend to synchronize or copy each other's movements. This tendency appears to be associated with pro-social attitudes and behavior [8,9,11,14,30] and to be influenced by the social setting (e.g., stronger synchronization when involved in a collaborative task [11,27]). Conversely, moving in synchrony seems to foster cooperative ability [29,32]. Because this nonverbal interpersonal movement coordination can be affected in pathologies such as premature birth [5], autism [6,13] and schizophrenia [31], more detailed understanding of the underlying dynamics and mechanisms may potentially provide vital information for future movement-based clinical assessments or therapies (cf. [31]).

Apart from spontaneous synchronization tendencies, the interactions between persons within a dyad have been examined extensively for intended coordination. Interestingly, the observed coordination dynamics showed striking qualitative similarities to those of bimanual coordination within a single individual [19,21,22,26]. In particular, it was demonstrated that when two individuals coordinate the rhythmic movements of one of their limbs with one another, the in-phase and antiphase coordination patterns (i.e., synchronous movements in identical or opposite directions, respectively) could be stably performed. Furthermore, a gradual increase in movement frequency resulted in an abrupt transition from the less stable antiphase pattern to the more stable in-phase pattern [22]. Such transitions between stable states are a key characteristic of a nonlinear system of coupled oscillators [7], indicating that the attraction to stable coordination patterns and

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the transitions between them were due to interactions between the rhythmic movements of the individuals [22].

Attraction to stable coordination patterns (in particular, the in-phase and antiphase patterns) has been convincingly demonstrated by means of various analysis methods and dependent variables, such as mean relative phasing and its variability [16,20,24–26,28], critical frequency [22], cross recurrence analysis [19,27], cross-spectral coherence [11,20,24,25], and power spectral overlap [16]. Although these results are clearly in agreement with the assumption of a bilaterally coupled system (with both persons influencing each other), these analyses cannot reveal the extent to which each of the individuals contributes to the coordinative stability. In principle it is even possible that the observed coordination dynamics result from a unilaterally coupled system, with only one person adapting to the movements of the other. In the present study we examined interpersonal coupling in a head-on fashion, using a perturbation paradigm and accompanying analysis that were originally developed to determine the degree to which the left and right hand contributed to the stability of bimanual within-person coordination [3,4].

Using this method we determined whether, and to what extent, both persons adapted their movements in response to a mechanical perturbation of one person's arm. We were particularly interested to what extent the other (unperturbed) person would adjust his or her arm movements, thereby contributing to the return to the stable coordination pattern. Whereas phase adjustments in the perturbed arm's movements may result from both its own orbital (limit cycle) stability [2,10] and its coupling to the other person's movements, adjustments in the movements of the unperturbed arm are a direct result of its coupling to the perturbed arm's movements. Hence, by applying perturbations to one oscillating arm and examining the degree to which the (unperturbed) companion contributes to the subsequent phase adjustments, we can unravel how two individuals contribute to the adaptations in movement phasing that are necessary to re-establish the original coordination pattern.

2. Materials and methods

2.1. Participants

Twelve young adults (2 male, 10 female; age range: 19–23) participated in the experiment. Eleven participants were right-handed (laterality quotient [LQ] range: 71–100, based on a Dutch version of the Edinburgh handedness inventory [15]), and one was left-handed (LQ = −78). Twelve dyads were formed, with each participant figuring in two different dyads. All participants gave their informed consent prior to the experiment. The protocol was approved by the departmental ethics committee.

2.2. Apparatus

Participants were seated in pairs, with the right elbows opposite to each other (distance between their torsos: ca. 1.3 m; Fig. 1). Each right lower arm was positioned in a manipulandum that allowed rotation about the elbow in the horizontal plane only. Each manipulandum was mounted on a vertical rotation axis and could be adjusted so as to locate the participant's epicondylus medialis above this axis. Angular position was registered using hybrid potentiometers (Sakae, type 22HHPS-10, accuracy 0.2°, sample frequency: 300 Hz). Using a Digital Actuator Controller and a torque motor (developed by Fokker aerospace) the movements of either arm could be arrested instantaneously, by sudden application of 60 Nm friction. Movement frequency was prescribed by means of an auditory metronome, presenting two beeps per movement cycle (alternatingly 100-Hz and 200-Hz tones; tone duration: 50 ms).

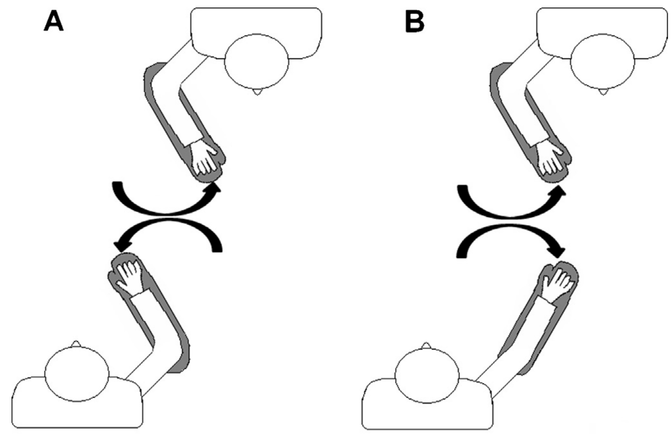

Fig. 1. Schematic representation of the experimental set-up and tasks. (A) Antiphase coordination and (B) in-phase coordination.

2.3. Procedure

Prior to the experiment, a practice period was administered. First, each participant practiced individually by moving the arm at the prescribed frequency (1.25 Hz), with the instruction to synchronize peak extension with one tone and peak flexion with the other. Next, the participants practiced as a pair (dyad). Both in-phase (simultaneous movements in the same direction) and antiphase coordination (simultaneous movements in opposite directions) of their arm movements were practiced (see Fig. 1), first without perturbation and subsequently with a perturbation of either arm (two trials: one perturbation per participant). The instruction was to restore the original coordination pattern as quickly as possible without pausing the movements. During these trials auditory pacing was presented at the start of the trial. Once the pattern was stably performed at the prescribed frequency, the experimenter waited for three more movement cycles and then terminated the pacing signal. The participants were instructed to continue their rhythmic movements in the same coordination pattern and at the same frequency.

In the experiment proper, the same perturbation paradigm was employed, involving a synchronization period (auditory pacing at 1.25 Hz) followed by a 30 s continuation period. During the continuation period a perturbation could be delivered to either arm (i.e., either participant). The order in which these perturbations were administered to the two arms was randomized. The perturbations were executed at the moment of peak extension and lasted a quarter cycle, resulting in a phase shift of 90° (for more details, see [3,18]). The timing of the perturbation was randomly distributed between the 12th and the 20th movement cycle of the continuation period. Again the instruction was to re-establish the original coordination pattern as quickly as possible, without pausing the movements. To further secure unpredictability of the perturbations, dummy trials without perturbation were also presented. The two coordination patterns (in-phase and antiphase) were performed in two separate blocks that were counterbalanced over the dyads. Within each block the three perturbation conditions (perturbation of participant 1, perturbation of participant 2, and no perturbation) were all presented 4 times, in a random order. Hence, each dyad performed $2 \times 3 \times 4 = 24$ trials in total. These trials were conducted in a single session of about 30 min. The time interval between the two measurement sessions per participant (each participant was engaged in two dyads, see Section 2.1) varied between 45 min and 2 days.

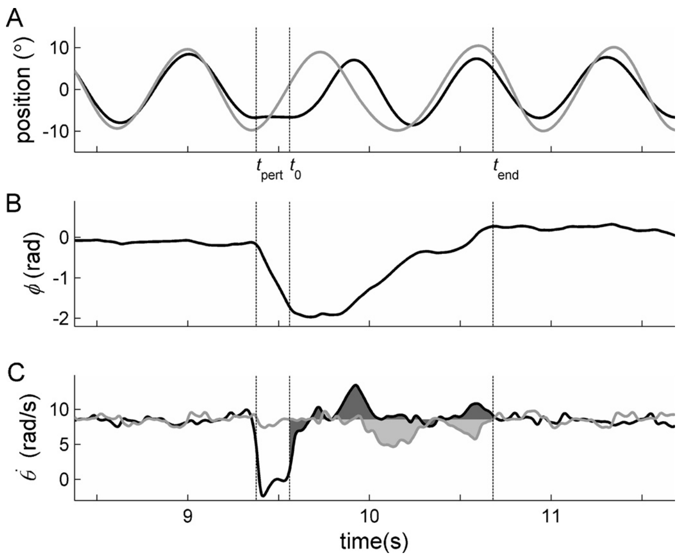

Fig. 2. Illustration of the successive steps in the derivation of IC_{NP}, based on a single representative trial (IC_{NP} = .61). Dashed vertical lines represent the moments of perturbation onset (t_{pert}), arm release (t_0) and end of relaxation (t_{end}). (A) Angular arm positions of the perturbed (black line) and unperturbed (gray line) agent. (B) Relative phase trajectory. (C) Phase velocities $\dot{\theta}$. Gray-shaded areas illustrate the amount of adjustment made by each agent: dark gray = perturbed agent; light gray = unperturbed agent. Increase in $\dot{\theta}$ reflects speeding up, decrease in $\dot{\theta}$ reflects slowing down.

2.4. Data analysis

The continuation periods of the 192 trials in which a perturbation was applied were analyzed. The analysis was adapted from De Poel et al. [3]. Angular position data of both arms were low-pass filtered (bi-directional second-order Butterworth filter, cut-off frequency: 10 Hz) and subsequently high-pass filtered (bi-directional second-order Butterworth filter, cut-off frequency: 0.1 Hz) to remove slow variations in the center of oscillation. The continuous phase angle (θ, in degrees) was derived for each arm, according to $\theta_i = \tan^{-1}(\dot{x}_i/x_i)$, with x_i denoting angular position, $\dot{x}_i$ denoting angular velocity (normalized to angular movement frequency [1]), and i indicating the sample index. Continuous relative phase between the arms for each sample (ϕ_i) was defined as the phase difference between the two arms.

Seventeen trials (<9%) were excluded from further analysis because of (i) incorrect movement frequency (>15% deviation from the prescribed frequency); (ii) incorrect phase relation prior to or after the perturbation (>45° deviation from the required phase relation); (iii) phase wrapping (unequal number of movement cycles by the two arms); (iv) no stable coordination pattern after perturbation (criterion: see below); and (vi) disruption of movements after perturbation (based on visual inspection).

For the remaining trials the degree to which the unperturbed arm altered its phasing in response to the perturbation was calculated as follows. First, for each trial the relevant trial segment was determined (cf. Fig. 2), which started when the arrested arm was released (t_0) and ended when the initial coordination pattern was re-established (t_{end}). The latter moment was determined by comparing the post-perturbation values of $\phi_{post,i}$ and the corresponding circular standard deviation ($SD\phi_{post,i}$, derived over a 21-point window centered around sample i [12]) to their mean values preceding the perturbation (i.e., ϕ_{pre} and $SD\phi_{pre}$; determined for the time interval from 1 s after the start of the continuation period to 1/3 s prior to the perturbation onset). The return process was deemed to have ended when (i) $\phi_{post,i}$ fell within the tolerance range $\phi_{pre} \pm 13.5°$ (with 13.5° corresponding to SD_{pre} averaged over all trials) and (ii) $SD\phi_{post,i} \leq SD\phi_{pre}$.

During the return period, changes in phasing in one or both arm movements had to occur in order to re-establish the original coordination pattern. To determine each individual's contribution to this process the changes in phasing were determined for each arm separately. Specifically, the rate of change in θ during the return period (i.e., phase velocity $\dot{\theta}_{return}$) was compared to the average rate of change prior to and after this period (i.e., $\bar{\dot{\theta}}_{average} = (\bar{\dot{\theta}}_{pre} + \bar{\dot{\theta}}_{post})/2$, with $\bar{\dot{\theta}}_{pre}$ being averaged over the 1000 samples [i.e., ca. 3.3 s] prior to perturbation onset and $\bar{\dot{\theta}}_{post}$ over the 1000 samples following t_{end}). Comparison of $\bar{\dot{\theta}}_{average}$ to the actually observed phase velocity during the return period yielded the degree of phase adaptation ($\Delta\bar{\dot{\theta}}$) for the arm in question: $\Delta\bar{\dot{\theta}} = \bar{\dot{\theta}}_{average} - \bar{\dot{\theta}}_{return}$ [3]. Hence, $\Delta\bar{\dot{\theta}} > 0$ indicated that the arm slowed down during the return period, whereas $\Delta\bar{\dot{\theta}} < 0$ indicated that it speeded up.

Finally, the relative contribution of the unperturbed arm to the return process was expressed using the index of coupling (IC_{NP}):

$$IC_{NP} = \frac{\Delta\bar{\dot{\theta}}_{NP}}{|\Delta\bar{\dot{\theta}}_{P}| + |\Delta\bar{\dot{\theta}}_{NP}|}$$

with NP and P referring to the unperturbed and perturbed arm, respectively. For each trial IC_{NP} (ranging from −1 to 1) reveals the degree to which phase adaptations in the unperturbed arm contributed to the return process. $IC_{NP} = 0$ indicates that the unperturbed arm did not participate in the return process, implying that only the perturbed arm adjusted its phasing. A bilateral coupling between the arms, however, was expected to result in deceleration of the unperturbed arm to 'wait for' the perturbed arm ($IC_{NP} > 0$), thereby reducing the effect of the perturbation onto the coordination between the two arms. Acceleration of the unperturbed arm ($IC_{NP} < 0$) was not expected to occur, because this would counteract the return to the initial coordination pattern. $|IC_{NP}| < .5$ indicated that the perturbed arm adapted more than the unperturbed arm, whereas for $|IC_{NP}| > .5$ the reverse was true.

The thus obtained IC_{NP} values were averaged per participant (over trials and sessions) to obtain mean values for each coordination pattern. The statistical analyses focused on whether (i) unperturbed participants contributed significantly to the restoration of the coordination pattern; (ii) perturbed and unperturbed participants contributed to this process to different degrees; and (iii) their relative contributions were affected by the coordination pattern that was performed.

3. Results

For all participants the mean values of IC_{NP} (averaged over trials and sessions) were larger than 0 (see Table 1). Using one-sample t-tests it was confirmed that for both in-phase ($t(11) = 11.66$, $p < .001$) and antiphase coordination ($t(11) = 8.45$, $p < .001$) IC_{NP} was significantly larger than 0, indicating that the movements of the unperturbed arm slowed down when the other arm within the dyad was perturbed. In order to test whether both agents contributed equally to re-establishing the coordination between them, we determined whether the absolute mean values of IC_{NP} differed significantly from .5 using one-sample t-tests. For both in-phase and antiphase coordination the values did not differ significantly from .5, indicating comparable contributions of both participants within the dyad. We also tested whether the phase adjustments by the unperturbed arm was different between the two coordination patterns. However, a paired t-test on the mean values of IC_{NP} did not reveal a significant difference.

Table 1
Mean IC_{NP} per participant and coordination pattern (averaged over trials and sessions).

Participant	In-phase	Antiphase
P1	.44	.19
P2	.40	.50
P3	.53	.51
P4	.41	.37
P5	.13	.26
P6	.43	.28
P7	.55	.72
P8	.36	.41
P9	.52	.46
P10	.64	.67
P11	.32	.23
P12	.45	.62
Mean	.43	.44

4. Discussion

Using a perturbation paradigm we examined the way in which two individuals in a dyad cooperate to maintain a stable coordination pattern. The results clearly showed that the person that was not perturbed also adapted his or her movement phasing, thereby contributing to re-establishing the shared coordination pattern. In general, the unperturbed agent's arm slowed down significantly, thereby alleviating the phasing adjustments required in the perturbed agent's arm movements (which had to speed up after the arrest). Hence, the coupling between the companions was bidirectional and subserved the stability of the interpersonal coordination pattern.

Although on average the contribution of the unperturbed arm was slightly smaller than that of the perturbed arm, this difference was not significant (viz. IC_{NP} was not significantly different from 0.5). Hence, the phase adaptations induced by our asymmetrical manipulation (viz. perturbation applied to one arm) revealed that in our dyads the strength of coupling between the companions was near symmetrical. This appeared to be the case for both in-phase and antiphase coordination. At first sight this result may seem counterintuitive, given the well-established stability difference between these coordination patterns [19,21,28]. However, IC_{NP} provides a relative rather than absolute measure of coupling strength, thereby precluding interpretations regarding the strength of coupling per se [17]. Hence our results indicate that, although the overall strength of coupling may have varied between the coordination patterns, the balance in the coupling influences between the two agents did not vary as a function of the required relative phasing between the arms.

The current results show that the degree to which a person's movements are affected by their coupling to a companion's movements can indeed be assessed using the applied methodology. This provides a new perspective for studying the degree to which individuals are influenced by another person's movements. It seems likely that the degree to which two agents contribute to a common coordination pattern may also be asymmetrical, e.g., due to differences in social competence or given a particular task setting. In analogy to the way in which the inherent asymmetry in bimanual coordination due to handedness has been unraveled in terms of asymmetrical coupling strength [3], this methodology may be applied to assess differences in interpersonal coupling associated with, for instance, social competence scores [23], social value orientation [11], or social impairments as observed in autism spectrum disorder (ASD [6]) and schizophrenia [31]. For instance, asymmetries in coupling strength (indexed by absolute IC_{NP} values deviating from .5 and different IC_{NP} values for the two participants) may be expected for dyads in which an individual with ASD and a healthy control participant coordinate their movements. As such, the present methodology may serve as a basis for a new evaluation tool for social impairments, which may provide a useful addition to conventional tests as the observed phase adaptation tendencies cannot easily be circumvented by acquired socially acceptable behavior. Similarly, the impact of imposed coupling asymmetries during collaborative task performance may be assessed, for instance in relation to the division of to-be-coordinated subtasks over a dyad, the attunement of attention to the companion's movements [20], or pro-social versus pro-self instructions regarding the task goals [11]. Relating those findings to the achieved levels of task performance may provide valuable insights into how collaborative tasks may best be instructed or implemented.

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