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Stability and variability of acoustically specified coordination patterns while walking side-by-side on a treadmill: Does the seagull effect hold?

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ABSTRACT

To examine whether the Haken–Kelso–Bunz model for rhythmic interlimb coordination applies to walking side-by-side on a treadmill, we invited six pairs of participants to coordinate their stepping movements at seven prescribed relative phases (between 0° and 180°) to scan the attractor layout governing their coordination. Two auditory metronomes, one for each participant, specified the required relative phase. For each trial participants were instructed to synchronize their left heel strikes with the beeps of the metronome (2 min) and to continue walking after the metronome stopped (1 min). If the Haken–Kelso–Bunz model applies to interpersonal coordination during treadmill walking, then (1) the variability of in- and antiphase should be minimal, (2) intermediate relative phases should be attracted to either in- or antiphase, and (3) the absolute shift away from the required relative phase should be greatest for a required relative phase of 90°. Only the third of these hypotheses was confirmed, indicating that the dynamical model for rhythmic interlimb coordination does not readily apply, at least not generically or robustly, to interpersonal coordination during walking side-by-side on a treadmill.

In pairs or groups of people certain patterns of motor behavior can emerge spontaneously, indicating that individual movements are influenced by the perceived movements of others. For example, in a prolonged applause the audience may synchronize their clapping after a while [10]. Likewise, two people walking side-by-side may synchronize their stepping movements with each other [11,22,25]. In all likelihood, such instances of spontaneous interpersonal coordination are no coincidence, but rather manifestations of certain coordination principles that, apparently, hold among people. If so, what are these principles? In the present study we examined whether walking side-by-side involves a coordination principle similar to that governing rhythmic interlimb coordination, namely the Haken–Kelso–Bunz (HKB) model [3].

The HKB model describes stability-related aspects of interlimb coordination through a frequency-dependent potential function and a corresponding nonlinear system of coupled limit-cycle oscillators. Schmidt and colleagues demonstrated that this model also applies to instructed forms of interpersonal coordination [17–19], and it even seems to hold in situations where coordination is neither instructed nor necessary to fulfill task requirements, as when two persons are swinging a pendulum at a preferred pace while solving a puzzle [14] or when two persons are rocking comfortably side-by-side in rocking chairs [13]. In those cases the observed coordination was not strictly phase-locked but intermittent, i.e., epochs of attraction to in- or antiphase were interspersed with epochs of phase wandering. Although such intermittent coordination may still agree with the HKB model [6], its fluid, transient nature renders it difficult to experimentally manipulate relevant parameters and thus to test the model's predictions [12].

Spontaneous (i.e., uninstructed) coordination between two persons walking together is currently gaining considerable interest for both theoretical [4,22] and therapeutic [11,25] reasons. These studies underscore the transient nature of uninstructed interpersonal coordination: phase-locking waxes and wanes in time, and sometimes even disappears. In a previous study [22] we showed that phase-locked epochs vary greatly between pairs in terms of duration and number (see also [11]) and that stable solutions are often far removed from in- and antiphase coordination. In this study no differential stability between these basic coordination patterns was observed when participants were instructed to coordinate their stepping movements, as would be expected from the HKB model. The results did suggest that the stepping of two persons walking together becomes entrained to a certain extent, but provided no strong evidence that the observed interpersonal coordination abides by the HKB model.

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In the present study we sought to further resolve this issue by empirically assessing the layout of the attractor landscape governing the coordination between two persons walking side-by-side on a treadmill. Two previous studies on bimanual coordination [21,23] provided the paradigm for the current experiment. In both, participants were invited to tap their right and left index fingers in time with two visual metronomes. The frequencies of the metronomes were identical but their phasing was systematically varied, resulting in 10 relative phases ranging from 0° to 360°. By this variation of the state variable, i.e., relative phase, the entire attractor-layout was scanned. Yamanishi et al. [23] required participants to practice the specified patterns. Once learned the visual metronomes were turned off while participants were instructed to continue tapping the same pattern. In the study by Tuller and Kelso [21], in contrast, the visual metronomes were present at all times. Consistent with the HKB model it was found in both studies that intermediate relative phases were attracted towards in- or antiphase and that the latter two patterns exhibited less variability than intermediate relative phases, resulting in the so-called *seagull effect*, after the shape of the variability-relative phase plot [7]. In subsequent studies the paradigm proved a reliable window into examining the attractor landscape of bimanual coordination and changes therein with learning [2,5,20,24].

We applied the scanning procedure to probe the relative phase between the left legs of two persons walking side-by-side on a treadmill. Participants with similar preferred stride frequencies at a fixed walking velocity wore headphones, through which metronome beeps were presented, under the instruction to synchronize the footfalls of their left leg with the metronome beeps. We varied the phasing between the two metronomes to examine the stability properties of seven required relative phases ranging from 0° to 180°. If the HKB model applies to interpersonal coordination during walking side-by-side, then (1) the variability of in- and antiphase should be minimal, (2) intermediate relative phases should be attracted to either in- or antiphase, and (3) the absolute shift away from the required relative phase should be greatest for 90° phase difference.

Twelve persons (six males, six females; aged 18–32 years) participated in the experiment on a paid voluntary basis. The experiment was approved by the ethics committee of the Faculty of Human Movement Sciences, VU University Amsterdam, Netherlands. All participants gave their informed consent prior to participation.

Participants walked on a treadmill (3 m wide, 4 m long; Bonte Technology BV, Zwolle, Netherlands) at a speed of 4.5 km/h. Gait kinematics was recorded using a 3D-active-marker movement registration system (Optotrak 3020, Northern Digital Inc., Ontario, Canada). Small infrared-light emitting markers were placed on the heel of each shoe and tracked at 250 Hz by two Optotrak sensor-units. Two auditory pacing signals, with a constant phase difference and a frequency corresponding to the preferred stride frequency, were presented through two earmuffs (one per participant) with built-in stereo earphones (Bilsom 787).

In the first session participants walked individually to become accustomed to walking on the treadmill (10 min) and to determine their preferred stride frequency. Subsequently, the participants practiced walking on the beat of the metronome for 2 min (paced walking) and then continued walking for 2 min more without the metronome (unpaced walking). In the second session, held several days later, participants walked side-by-side. Six pairs were formed of participants with similar stride frequencies to minimize the effects of differences between individually preferred frequencies[1] and to optimize conditions for phase-locking to occur. Before the experiment proper, participants walked side-by-side to get used to walking on the treadmill (8 min habituation), and practiced walking to the metronome beat for 3 min (alternating paced with unpaced walking). During this habituation and practice period participants were not allowed to hear or see each other to prevent them from adapting their gait patterns to each other. Participants therefore wore earmuffs and looked to the side opposite to where the other person was walking. After a short break and 3 min of 'regular' side-by-side walking, participants performed seven experimental trials. Each trial consisted of 2 min of paced side-by-side walking at a constant phase difference as specified by the metronomes and 1 min of unpaced continuation. Participants were instructed to synchronize their left heel strikes with the metronome beeps and to continue walking in the same manner after the metronome stopped. The required phase differences were 0°, 30°, 60°, 90°, 120°, 150°, and 180° (values were converted to delays (in ms) and taken relative to the metronome frequency), and were presented in random order. Participants were instructed to look at a 10 cm × 10 cm white square located cross-diagonally 2 m in front of them to ensure that leg movements of the other participant were in the participant's visual field. They were instructed not to talk during recordings.

Time indices of the left heel strikes of both participants were determined by means of a peak-detection algorithm identifying the moment at which the vertical position of the heel marker reached its minimum. Stride frequency was defined as the inverse of the interval between two consecutive ipsilateral heel strikes. The point estimate of relative phase, i.e., the normalized difference between the moments of heel strike of the left feet, was defined as:

$$\varphi(i) = \frac{HS_{p2(i)} - HS_{p1(i)}}{HS_{p1(i+1)} - HS_{p1(i)}} \cdot 360^\circ$$

where $HS_{p1(i)}$ and $HS_{p2(i)}$ are the moments of heel strike at time i of the left foot of participants 1 and 2, respectively. $HS_{p1(i+1)} - HS_{p1(i)}$ denotes the time difference between two consecutive ipsilateral heel strikes of participant 1. Mean direction and circular variance of the relative phase were calculated from the mean resultant vector; circular variance was transformed to a linear scale to perform linear statistical analyses [8]. For the metronome paced walking an ANOVA with required relative phase as within-subject factor was performed, with repeated measures on mean error and absolute mean error between observed and required relative phase (i.e., phase shift and absolute phase shift), and relative phase variability (standard deviation). We tested whether the distributions for the unpaced continuation trials differed significantly from uniformity with the Hermans–Rasson test, which is powerful against both unimodal and multimodal alternatives. If significantly different ($p < 0.01$), then this indicates the existence of a preferred orientation. An ANOVA similar to the one used for the paced trials was not appropriate because of the transient nature of the data.

All relative phases observed across all participant pairs are shown in Fig. 1 in terms of relative phase distributions for both metronome paced (in purple, outside the circle) and unpaced walking (in grey, inside the circle) as a function of the seven required relative phases (indicated with the grey dial). For metronome paced walking, also the mean direction (indicated with the purple dial), and the length of the mean resultant vector (i.e., the longer the length of the purple dial, the more concentrated the data) are shown. The variance of relative phase was greatest for the 90° phase relation, where the observed relative phases were dispersed over a wide range, without a clear preference for the required phase relation. Furthermore, the shift away from the required relative phase and the dispersion of relative phases gradually increased from 0° to 90° and gradually decreased towards 180°, with a comparatively

[1] The differences in preferred frequency between members of a pair were 0.000, 0.000, 0.000, 0.017, 0.034, and 0.016 Hz, respectively.

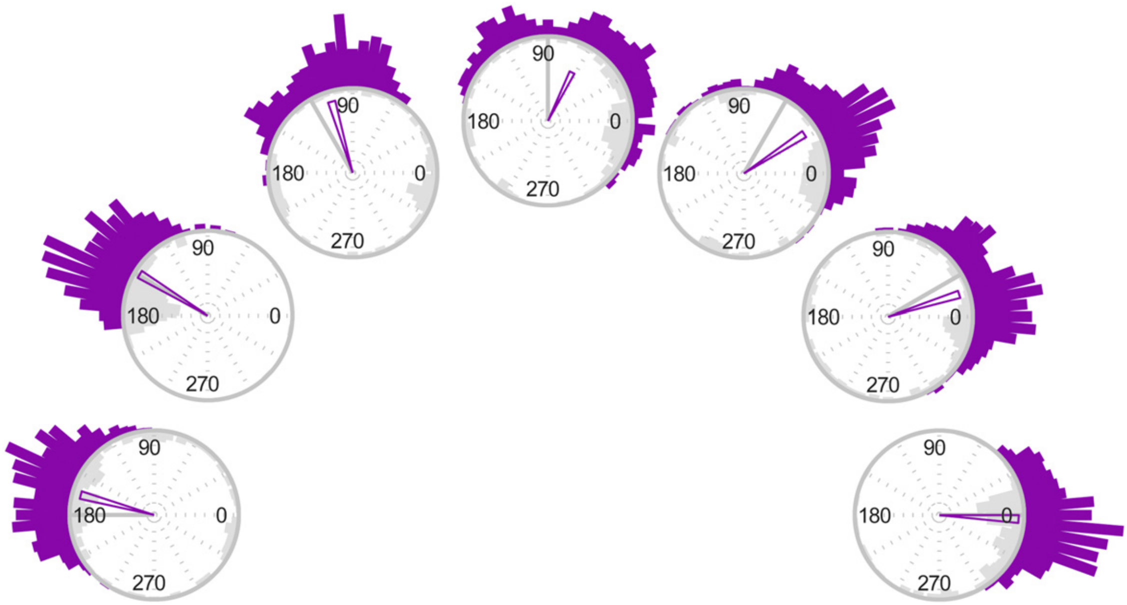

Fig. 1. Circular histograms showing the distributions of the observed relative phases (in °) for paced (purple bars outside circle) and unpaced walking (grey bars inside circle) as a function of the required relative phase (indicated by the grey dial). For paced walking, the purple dial indicates the central tendency of the distribution, while its length represents a measure of distribution concentration.

good performance at 150°. These first impressions were examined further by means of ANOVA.

There was a significant effect of required relative phase on the mean phase shift, $F(6, 30) = 3.00$, $p < 0.05$, $\eta_p^2 = 0.38$. As is evident from Fig. 2A, the observed relative phase was in general smaller than the required relative phase, especially for required relative phases around 90°. Contrast analyses did not yield any significant differences across the individual levels of the required relative phase. Importantly, the observed deviation in required relative phase for 30° and 60° was consistent with the model prediction as the negative sign implies attraction to in-phase coordination; by the same token, however, no attraction to antiphase was present. Furthermore, there was a significant effect of required relative phase on the absolute phase shift, $F(6, 30) = 4.52$, $p < .01$, $\eta_p^2 = 0.48$. Here, contrast analyses revealed a significant quadratic trend, $F(1, 5) = 17.91$, $p < 0.01$, $\eta_p^2 = 0.78$, indicating small shifts away from the required relative phase near 0° and 180°, and large shifts away from the required relative phase near 90° (see Fig. 2B). No significant effects of required relative phase on variability (standard deviation of relative phase) were found ($p > 0.1$).

The grey bars inside the circle of Fig. 1 indicate how the observed relative phases varied during unpaced continuation. For the required relative phases of 0°, 30°, and 60° a clustering near in-phase was observed, while for the required relative phase of 150° a clustering near antiphase was observed; in contrast, for the required relative phases of 90°, 120°, and 180° no pronounced clustering was evident. These observations suggest that in some cases participant pairs were attracted to either in- or antiphase coordination. In order to verify these observations statistically the distributions of relative phase were tested for uniformity for each pair and relative phase condition using the Hermans–Rasson test; see Table 1. In 10 cases the relative phases were uniformly distributed (i.e., no directionality), in 12 cases a multimodal distribution without marked directions was observed, and in 20 cases a clear unimodal preference for a particular direction, mostly near 0° and 180°, was observed.

We employed a scanning procedure to probe the relative phase between the left legs of two persons walking side-by-side on a treadmill to gain further insight into the applicability of the HKB model. The HKB model describes the stability-related aspects of interlimb coordination by means of a frequency-dependent potential function and a corresponding nonlinear system of coupled limit-cycle oscillators. By systematically manipulating the model's parameters (by gradually increasing movement frequency), the hallmarks of the HKB model have been repeatedly found in a huge number of studies covering various experimental settings, including instructed and uninstructed interpersonal coordination. In the present study we found that (1) relative phase variability was not markedly lower for in- and antiphase coordination, (2) during paced walking in-phase coordination attracted nearby relative phases, whereas antiphase coordination did not, while during unpaced walking both in- and antiphase coordination appeared attractors, and (3) in terms of absolute error, walking at a required relative phase of 90° was indeed the most difficult condition.

Admittedly, as regards hypothesis (1), it seems conceivable that the absence of the seagull shape in the variability-relative phase plot was due to a lack of power: on the face of it, the predicted shape appeared to be present to a degree. However, even if the seagull shape would become more prominent with increasing power, stronger manifestations of the essential features of the HKB model should have been observed to support the theoretical position that it dictates the coordination between persons walking side-by-side on a treadmill.

This conclusion is motivated further from several findings pertaining to hypothesis (2). First of all, during paced walking some

Table 1
Results from the Hermans–Rasson test for unpaced walking. A non-significant result (ns) implies a uniform distribution, while a significant result implies a uni- or multimodal distribution. Since the mean direction of a multimodal distribution (multi) is meaningless, only mean directions (in °) of unimodal distributions are presented. Unimodality was defined as a distribution with a mean resultant length >8.

Pair	Required relative phase						
	0°	30°	60°	90°	120°	150°	180°
1	ns	multi	multi	−4	ns	161	ns
2	−1	−3	91	multi	ns	171	177
3	−28	multi	multi	−25	−5	167	multi
4	multi	ns	−2	ns	ns	169	163
5	5	multi	ns	multi	−167	169	multi
6	6	−20	4	multi	ns	ns	multi

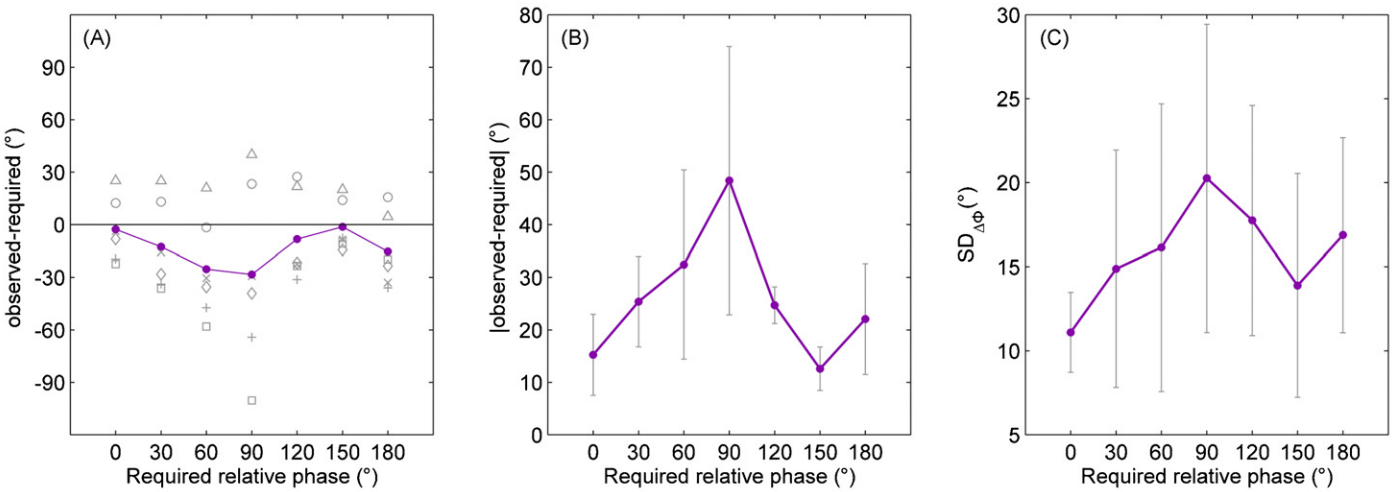

Fig. 2. Mean error (A) and absolute mean error (B) between observed and required relative phase, and relative phase variability (C) as a function of the required relative phase. The symbols in (A) represent different pairs.

attraction to in-phase coordination was observed, but not to antiphase coordination, which is inconsistent with the HKB model. Furthermore, unpaced continuation displayed a variety of behaviors, ranging from no coordination at all (uniform distribution) to a clear preference for either in- or antiphase coordination,[2] suggesting that the HKB model was only weakly operative at best. Finally, we found that the overall performance during paced walking was remarkably good for a required relative phase of 150° (even for the required relative phase of 180° there was a tendency towards 150°), while during unpaced walking five out of six pairs showed a relatively consistent shift of 10–20° from the initial orientation at 150° towards antiphase coordination. The difference in the relative phase distribution between paced and unpaced walking around 150° suggests that a "symmetry breaking term" was present that was more prominent during paced than during unpaced walking. How and why this would be so, however, cannot be distilled from the present data.

Hypothesis (3) was that a required relative phase of 90° would be the most difficult to perform, as it represents an unstable fixed point. Although this was not confirmed by the ANOVA for relative phase variability, both the relative phase distributions depicted in Fig. 1 and the statistical results for the mean absolute error indicated that pairs experienced most difficulties in maintaining a 90° phase difference.

Overall, one may conclude that the present results only contain weak hints for the applicability of the HKB model to walking side-by-side on a treadmill. This conclusion is in line with our previous study [22], but arrived at here using an entirely different approach, thus extending the evidence. In principle, there are two possibilities why the HKB model may have limited applicability in studying walking side-by-side. The first possibility is that interactions during walking side-by-side on a treadmill are in fact HKB-like but were simply too weak to induce the expected characteristics in a consistent and robust manner. The second is that interactions during walking side-to-by-side are of an essentially different nature than those governing the interlimb coordination for which the HKB model was originally designed.

[2] In all fairness, it is important to note that, in contrast to the study of Yamanishi et al. [23], our participants received no feedback on how well they performed the relative phase coordination task, nor were they trained to produce the specified patterns. This might explain why participant pairs in our study were relatively poor in maintaining the required phase relation after the metronome was turned off.

As regards the first possibility it is noteworthy that in the literature on rhythmic bimanual coordination within a person, three sources of interlimb interaction are distinguished that are associated with movement planning, error correction, and reflex-like behavior, respectively [15,16]. The distinction between these sources is based on their sensory dependence and intentionality: movement planning is afference-independent and intentional, and involves the integrated timing of feed-forward signals to both limbs; error correction is afference-dependent and intentional, and involves timing corrections based on perceived errors in relative phase; and the reflex-like behavior is afference-dependent and unintentional, and involves phase entrainment of a limb by sensory signals resulting from the movements of another limb. All sources enhance the stability of in- and antiphase coordination patterns, but only movement planning (and to a lesser degree error correction) was found to contribute to the stability difference between these patterns. In uninstructed interpersonal coordination, people do not intentionally coordinate their movements, leaving phase entrainment as the only form of interaction. This may explain the weak coupling observed in this kind of coordination, as well as the absence of marked differences in the stability of in- and antiphase coordination (cf. [22]). For the latter result we note that in walking side-by-side in- and antiphase coordination may have been equally stable because in this case there are not just two oscillators as in bimanual coordination but two pairs of oscillators (i.e., two pairs of legs). That is, an antiphase solution is always accompanied by an in-phase solution and vice versa. It might have also been the case that participants walked more cautiously, and with a stronger attentional focus on locomotion itself, on the treadmill than they would when walking overground (although there was a long familiarization period before the actual trial recording). It must therefore be acknowledged that treadmill walking may have provided an unfavourable context for testing the validity of the HKB model for interpersonal coordination, implying that the present results and conclusions should be taken specifically in reference to walking side-by-side on a treadmill, until they are replicated for overground walking.

Several studies showed at least some interpersonal entrainment of gait patterns [4,11,22,25]. Besides an underlying sensory-based coordination principle, such entrainment may reflect the activity of cognitive processes. Both anecdotal and empirical findings suggest that moving in synchrony with one another may induce feelings of unity, harmony, and/or may enhance memory storage (e.g. [1,9]). These psychological benefits may not only be a consequence of synchronized behavior, but also motivate spontaneous synchronization when walking side-by-side in the first place.

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