Available online at www.sciencedirect.com
ScienceDirect
Neuroscience Letters xxx (2008) xxx–xxx
Neuroscience Letters
www.elsevier.com/locate/neulet

Characteristics of instructed and uninstructed interpersonal coordination while walking side-by-side☆

Niek R. van Ulzen [a,*], Claudine J.C. Lamoth [b], Andreas Daffertshofer [b], Gün R. Semin [a], Peter J. Beek [b]

[a] Department of Social Psychology, VU University Amsterdam, Van der Boechorststraat 1, 1081 BT Amsterdam, The Netherlands
[b] Research Institute MOVE, Faculty of Human Movement Sciences, VU University Amsterdam, The Netherlands

Received 12 September 2007; received in revised form 6 November 2007; accepted 15 November 2007

Abstract

We examined how people synchronize their leg movements while walking side-by-side on a treadmill. Walker pairs were either instructed to synchronize their steps in in-phase or in antiphase or received no coordination instructions. Frequency and phase analysis revealed that instructed in-phase and antiphase coordination were equally stable and independent of walking speed and the difference in individually preferred stride frequencies. Without instruction we found episodes of frequency locking in three pairs and episodes of phase locking in four pairs, albeit not always at (or near) 0° or 180°. Again, we found no difference in the stability of in-phase and antiphase coordination and no systematic effects of walking speed and the difference in individually preferred stride frequencies. These results suggest that the Haken–Kelso–Bunz model for rhythmic interlimb coordination does not apply to interpersonal coordination during gait in a straightforward manner. When the typically involved parameter constraints are relaxed, however, this model may largely account for the observed dynamical characteristics.

Keywords: Interpersonal coordination; Synchronization; Entrainment; Relative phase; Walking

When two persons are walking side-by-side, their walking movements appear not to be independent of each other but coupled to a degree. Such coupling may yield signs of entrainment possibly interspersed by episodes of phase wandering and cycle slipping [9]. Zivotofsky and Hausdorff [23] provided preliminary empirical evidence for uninstructed, or spontaneous, synchronization between walking partners. They studied 14 participant pairs walking side-by-side under various sensory feedback conditions. Although participants were not asked to walk in synchrony, entrained walking was observed in nearly half of the trials. Synchronization was indexed by assigning a subjective score to conventional video recordings without any further unbiased quantification. Synchronous in-phase walking occurred most often when tactile feedback was present (i.e., simultaneous stepping of homologous legs, viz. left–left and right–right). Remarkably, entrained walking was also observed without any feedback, where antiphase synchronization prevailed (i.e., simultaneous stepping of non-homologous legs, viz. left–right and right–left). To our knowledge, Zivotofsky and Hausdorff [23] were the first to report empirical evidence of uninstructed synchronization while walking in pairs. However, as the authors argue, the evidence provided was rather limited, both in terms of empirical data and corresponding analyses. Walking movements were not measured as such and the simple scoring of synchronization was based solely on the observation of step moments, so that the generating dynamics were entirely ignored. Here, we sought to understand the emergence of entrainment against the background of the dynamical qualities of its generating components, i.e., participants and their walking patterns, by studying more detailed dynamical characteristics of walking patterns in terms of (time-resolved) frequency and phase locking.

As conceptual backdrop for our study we adopted a well-established theoretical model for rhythmic interlimb coordination, namely that of Haken et al. [5], because this model has been claimed to apply to instructed and uninstructed interpersonal coordination as well. In brief, this model describes the dynamics of the relative phase between two oscillatory end-

☆ This study was supported by the Royal Netherlands Academy of Arts and Sciences (ISK/4583/PAH) and the Dutch Science Foundation (NWO, grant 051.02.090).
* Corresponding author. Tel.: +31 20 5988871; fax: +31 20 5988921.
E-mail address: NR.van.Ulzen@psy.vu.nl (N.R. van Ulzen).

0304-3940/$ – see front matter © 2008 Elsevier Ireland Ltd. All rights reserved.
doi:10.1016/j.neulet.2007.11.070

effectors that displays two stable solutions at low movement frequencies: one at 0° and the other at 180°, reflecting in-phase and antiphase coordination, respectively. When movement frequency is gradually increased, the stability of both coordination modes decreases. Beyond a critical frequency, however, only in-phase coordination remains stable. Inclusion of a so-called detuning term, i.e., a component that represents the difference in the participating oscillators' natural frequencies, yields systematic shifts away from 0° and 180° [21] as well as (differential) changes in stability [3,4]. The predicted features were observed repeatedly in several studies of interlimb coordination within a person, usually involving simple rhythmic movements of two limbs (e.g., [4,6–8]). Those features were further observed in various instructed forms of interpersonal interlimb coordination [1,11,15,16,18,20], although both in-phase and antiphase coordination proved less stable when produced by two persons compared to one [17]. The latter observation implies that the degree of coupling is weaker between persons than within a person, presumably because certain neurally based (e.g., proprioceptive) interlimb interactions are absent between persons. For uninstructed interpersonal coordination participant pairs exhibited intermittent coordination, i.e., spells of attraction to certain phase relations, but no strict phase locking, implying that the interlimb coupling was not sufficiently strong to overcome differences between individually preferred movement frequencies (e.g., [13,16]).

Interpersonal coordination during daily-life activities is currently gaining interest. For example, Richardson and colleagues [14] found evidence for instructed and uninstructed interpersonal coordination between two people swaying side-by-side in rocking chairs, while Zivotofsky and Hausdorff [23] explored uninstructed coordination when walking side-by-side. In the present study, we examined to what extent entrainment during walking side-by-side reflects the fundamental dynamical properties of interlimb coordination as captured by the Haken–Kelso–Bunz model. In particular, by using a 3D movement registration system and time-resolved frequency and phase analyses, we studied the following questions: when instructed, are in-phase and antiphase coordination differentially stable? Does frequency entrainment between walking participants depend on walking speed and the difference in preferred stride frequency between walkers? When uninstructed, how persistent is entrainment, and how does it depend on walking speed and individually preferred stride frequencies? Are in-phase and antiphase the only stable phase relations, and are they differentially stable?

By addressing those questions, we expected to strengthen the empirical evidence for entrainment during walking side-by-side, to gain theoretical insight into its dynamical signatures and constituents, and to evaluate the potential of the Haken–Kelso–Bunz model as a possible theoretical account of the phenomena of interest. As regards the latter aspect, it should be appreciated that the Haken–Kelso–Bunz model represents a system of two coupled oscillators, whereas walking side-by-side involves four oscillating (lower) limbs. However, by assuming, at least as first pass on the problem, that the two by two oscillators of the walking pair display mirror symmetry, this four-oscillator system may be formally reduced to a two-oscillator system [2].

Twenty-two persons (10 males, 12 females; aged 18–32 years) without walking disabilities participated in this study on a paid voluntary basis. The experiment was approved by the ethics committee of the Faculty of Human Movement Sciences, VU University Amsterdam, and all participants gave their informed consent prior to participation. Participants with different stride frequencies were coupled to form 11 pairs (6 of mixed gender, 2 males, and 3 females).

Participants walked on a treadmill (3 m wide, 4 m long; Bonte Technology BV, Zwolle, The Netherlands). Movements of left and right lower legs were recorded with a 3D-active-marker movement registration system (Optotrak 3020, Northern Digital™, Ontario, Canada). Small lightweight custom-made triangular frames with three LED-markers affixed at each corner of the frames were attached dorsally on the lower legs using elastic neoprene-fabric bands with Velcro strips. This resulted in six markers per person sampled at 170 Hz. Throughout the experiment participants wore sneakers or sport shoes.

In two experimental sessions, several days apart, participants performed four trials. Before each session, participants were acquainted with walking on a treadmill by walking for 8 min on the treadmill at several speeds. Subsequently, a reference measurement was performed to assess the markers' positions. Each trial lasted 8 min and every 2 min the walking speed increased by 1.1 km/h resulting in four speeds (2.8, 3.9, 5.0, and 6.1 km/h). In the first session, participants walked individually to assess their preferred stride frequency. Pairs were then formed of participants with different stride frequencies. The second session consisted of three trials with a 2-min break between trials, during which participants walked side-by-side. First, they walked together without any instructions about their gait pattern (uninstructed coordination condition) or information about the purpose of the experiment (interviews after the experiment revealed that participants were indeed ignorant in this regard). This trial always preceded the two other trials to keep them naive about the purpose of the experiment. Then, in two counterbalanced trials, participants were instructed to synchronize their steps (instructed coordination condition), in either in-phase (i.e., left–left, right–right) or antiphase coordination (i.e., left–right, right–left). Those trials were included to be able to compare the stability of in-phase and antiphase interpersonal coordination during walking and to assess the effects of walking speed on the stability of those modes, as well as to identify the effects of the difference in the individually preferred stride frequency on the location of the fixed point of relative phase (phase shift $\delta\phi$) and its stability (as prompted by the model [5]). We expected that this part of the experiment would help to pinpoint dynamical characteristics of uninstructed interpersonal coordination.

Participants were instructed to walk as naturally as possible and to fixate their gaze on a 10 cm × 10 cm white square located cross-diagonally 2 m in front of them. Through this requirement we ascertained that leg movements of a person were in the periphery of the other person's visual field. Participants were asked not to talk during recordings. To avoid trivial instances of interpersonal coordination, participants adopted different starting positions for each trial: one participant started a meter in front of the eventual walking position, whereas the other started a meter behind the eventual walking position (the starting positions were randomized across trials). As soon as the treadmill started to move participants were requested to walk to the same level on the treadmill whereupon movement registration started.

From the reference measurements a global *xyz*-Euclidian frame was defined: the *x*-axis pointed in the walking direction, the *y*-axis was horizontal perpendicular to *x*, and the *z*-axis pointed vertically upwards. Subsequently, the rotation of marker frames around the *y*-axis was calculated yielding rotational movements of the lower legs in the sagittal plane. The instantaneous frequency of these signals was calculated with a short-time Fourier transform. Movement frequency (i.e., stride frequency) was identified as the frequency with the largest peak in the (time-resolved) power spectrum (estimates were verified through visual inspection of the original time-series). Frequency locking was present whenever the mean frequency difference over a sliding 5-s-window was smaller than 2×10^{-4} Hz provided that the absolute value of detuning $|\Delta\omega|$ never exceeded 2×10^{-2} Hz. To obtain time-resolved relative phases between the legs, signals were band-pass filtered (fourth order bi-directional Butterworth filter) using an individual frequency-band centered around the movement frequency (0.70 × minimum movement frequency, 1.25 × maximum movement frequency). Then the analytical signal was computed via the Hilbert transform and its phase was used as instantaneous phase (see e.g., [12]). Mean and standard deviations of the relative phases, i.e., the phase difference between the left lower legs, were computed only for frequency-locked periods because for non-frequency-locked periods the relative phase may wrap continuously between 0° and 360°, rendering mean and standard deviation meaningless. Mean and variance of the relative phase were calculated using circular (i.e., directional) statistics, and circular variance was transformed to linear standard deviation [10].

The analysis of in-phase and antiphase coordination entailed testing whether in-phase coordination was more stable than antiphase coordination, whether stability changed with increasing speed, and whether phase shifts away from the intended phase relation depended lawfully on detuning. One pair was excluded from the analyses due to technical problems during the instructed coordination trials. A two (coordination mode) × four (speed) ANOVA on the standard deviation of the relative phase revealed no significant effects ($p = .20$ and .27 for coordination mode and speed, respectively). To verify if the phase shift away from the intended phase depended on detuning $|\Delta\omega|$, we performed a regression analysis with the detuning as predictor variable and the phase shift in in-phase and antiphase patterns as outcome variables. No significant effects were found, neither for the in-phase pattern, $\beta = .19$, $t(9) = 0.56$, $p = .59$, nor for the antiphase pattern, $\beta = .28$, $t(9) = 0.83$, $p = .43$ (see also Fig. 1). In addition, the correlation coefficients of in-phase and antiphase patterns were not significantly different, $t(7) = -0.28$, $p = .39$ [19,22]. These results imply that phase shifts were not dependent on detuning.

For each pair and walking speed, plots of the type depicted in Fig. 2 were made and inspected visually for (episodes of)

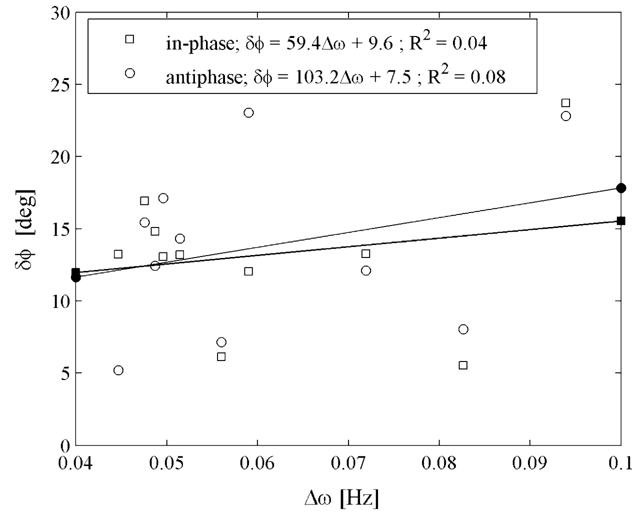

Fig. 1. Relation between phase shift $\delta\phi$ and detuning $\Delta\omega$ for instructed in-phase and antiphase coordination.

frequency and phase locking. From this initial, cursory analysis it was evident that frequency and phase locking was absent at all walking speeds in three pairs (Fig. 2, panels A1 and B1), while episodes of frequency locking (no pronounced phase locking) were present in three pairs (Fig. 2, panels A2 and B2) and episodes of both frequency and phase locking were present in the four remaining pairs, especially at lower walking speeds (Fig. 2, panels A3 and B3, A4 and B4). Pairs in which frequency and phase locking were absent altogether were excluded from subsequent analyses. For the remaining pairs ($n = 7$), we first tested whether the coupled mean frequency difference was smaller than the uncoupled mean frequency difference. A two (condition: uncoupled vs. coupled) × four (speed) repeated measures ANOVA revealed a significant effect of condition, $F(1, 6) = 10.60$, $p < .05$, $\eta_p^2 = .64$, and speed, $F(3, 6) = 3.48$, $p < .05$, $\eta_p^2 = .37$, indicating that the coupled mean frequency difference (0.029 ± 0.02 Hz) was indeed smaller than the uncoupled mean frequency difference (0.054 ± 0.02 Hz), and that the mean frequency difference increased with increasing speed (0.031 ± 0.02, 0.037 ± 0.02, 0.044 ± 0.03, and 0.055 ± 0.03 Hz, respectively).

The mean relative phase determined in episodes of frequency locking revealed that phase locking around in-phase and antiphase coordination in some but not all pairs (Table 1). Also other forms of phase locking were observed (Fig. 2, panels A4 and B4) showing phase locking around 46° and 221°. Notice that the shifts away from in-phase and antiphase coordination were not related to the difference in individually preferred stride frequencies. The same held for the standard deviation of relative phase during the aforelisted episodes of frequency locking. Table 1 summarizes the instances of phase locking at the various speed conditions in the walking pairs with frequency locking.

We examined the dynamical characteristics of interpersonally entrained walking using a well-established model as conceptual backdrop [5]. We first studied effects of walking speed and differences in individually preferred stride frequencies on

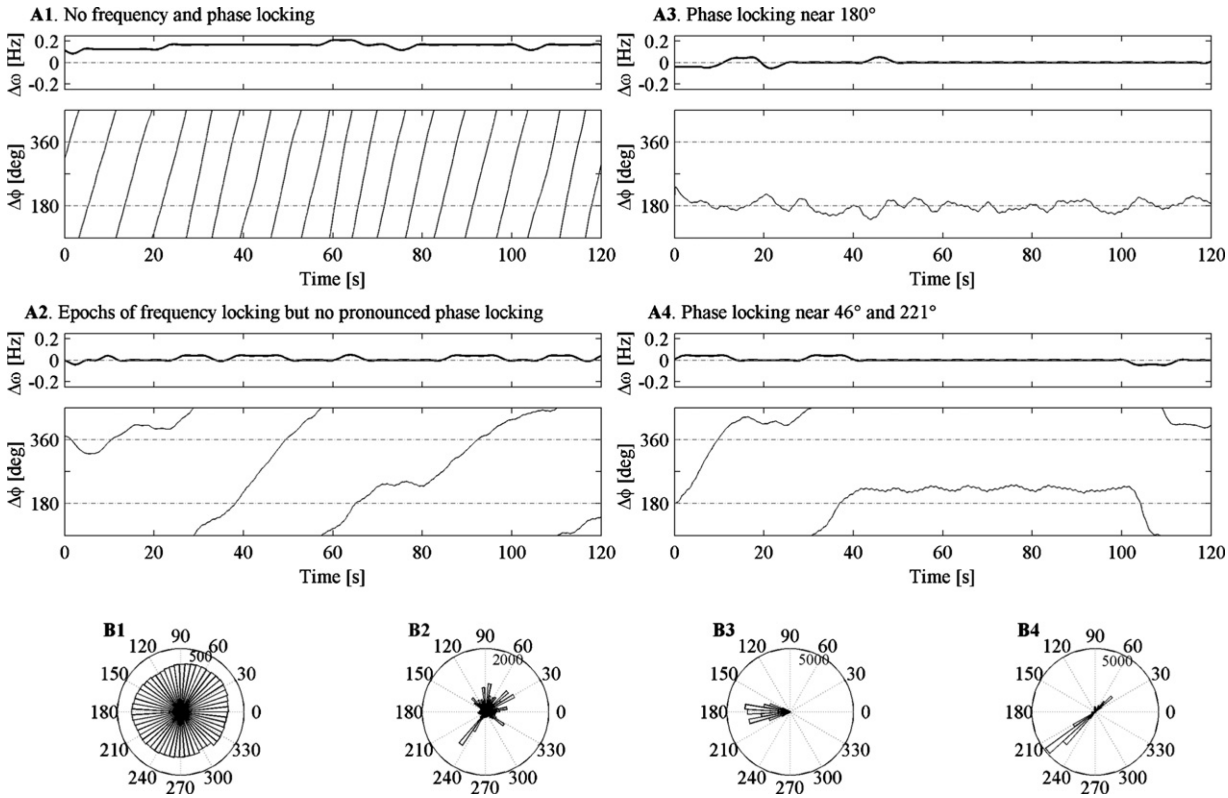

Fig. 2. Four cases of frequency and phase locking at one speed condition. Time-series of the frequency difference and the relative phase (A), and the accompanying phase distributions (B). Pair 6 did not show frequency or phase coupling (A1 and B1); pair 1 did show frequency locking but no consistent phase locking (A2 and B2); pair 3 showed frequency and phase locking at about 180° (A3 and B3); pair 7 showed frequency and phase locking near 46° and 221° (A4 and B4).

Table 1
Mean relative phase during episodes of frequency locking during uninstructed coordination trials

Pair	#EFL	Mean relative phase (°)			
		2.8 km/h	3.9 km/h	5.0 km/h	6.1 km/h
1	1	146	200	19	–
	2	–	357	237	–
2	1	197	–	–	48
3	1	204	179	49	13
	2	163	–	203	–
	3	179	–	–	–
5	1	353	–	–	–
7	1	23	46	50	204
	2	233	221	39	36
	3	–	–	–	218
9	1	354	350	2	–
	2	15	278	199	–
	3	–	–	–	–
11	1	166	342	251	–
	2	158	63	51	–

Seven pairs showed one or more episodes of frequency locking (#EFL ≥ 1) in at least one speed condition. For each episode the mean relative phase was calculated. If no episode of frequency locking was evident for a particular speed condition then this is indicated by '–'.

in-phase and antiphase coordination in trials in which the participants were explicitly instructed to instantiate those coordination modes. Contrary to model predictions, in-phase and antiphase coordination were equally stable, independent of walking speed and the difference in the individually preferred stride frequencies. In addition, the latter parameter appeared not to induce systematic phase shifts. Collectively, these results suggest that interpersonal coordination during walking does not abide by the prevailing model, with the caveat that in-phase and antiphase patterns may have been equally stable because participants could, in principle, always maintain a visual in-phase relation with one of the other's legs, regardless of whether it was homologous or not.

In the absence of instructions, we found clear evidence of entrainment during walking in pairs, with weaker and stronger manifestations across walker pairs. We also found that frequency and phase locking were not consistently present within walker pairs. First, entrainment waxed and waned in time. Using appropriate time-resolved techniques with a markedly higher resolution than video scoring, frequency and phase locking were found to be less prominent in our data than the near 50% reported by Zivotofsky and Hausdorff [23]. Second, we not only found in-phase and antiphase coordination, but also phase locking at other phase relations. This finding suggests that uninstructed interpersonal coordination during walking is governed by various coupling mechanisms, which should be unraveled in future studies.

Please cite this article in press as: N.R. van Ulzen, et al., Characteristics of instructed and uninstructed interpersonal coordination while walking side-by-side, Neurosci. Lett. (2008), doi:10.1016/j.neulet.2007.11.070

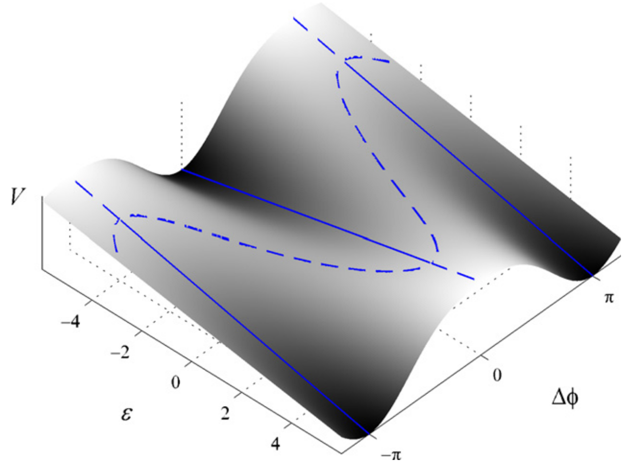

Fig. 3. Potential landscape $V(\Delta\phi) = \varepsilon \cos \Delta\phi - \cos^2 \Delta\phi$. For a fixed parameter ε stable solutions of the relative phase $\Delta\phi$ appear as (local) minima in the landscape (solid lines), whereas (local) maxima (dash lines) represent unstable solutions. If the bifurcation parameter ε decreases and passes the critical value $\varepsilon_{critical} = -4$, then the potential represents the classical transition from antiphase to in-phase [5]. If the parameter is large, however, this bifurcation diagram can be inverted—see text for more details.

When the analysis was confined to instances in which frequency and phase locking was present, no evidence was found that the model [5] would be applicable to uninstructed interpersonal coordination during walking. As for instructed synchronized walking, in-phase and antiphase coordination were not differentially stable (although the same caveat as mentioned above applies), and appeared independent of walking speed and differences in individually preferred stride frequencies. Furthermore, no relation between the latter factor and phase-locked values was found.

Taking those results at face value, one would be inclined to conclude that a principally different kind of dynamical model might be required to capture (un-)instructed interpersonal coordination during walking. It could also be the case, however, that entrainment was relatively weak and transient because sufficiently strong coupling mechanisms were lacking. Perhaps this rendered the observed modes less steady than they would or could be under other circumstances. The theory of coordination dynamics dictates that increases in coupling strength lead to more entrainment. The change in coupling strength in the Haken–Kelso–Bunz model is mediated by a drop in movement amplitude caused by an increase in movement frequency. For interpersonal coupling during walking this frequency/amplitude dependency is very different because increases in walking speed are achieved by increases in both step length (amplitude) and frequency. In principle, however, this does not render a dynamical model displaying differential stability inappropriate. For instance, using the mathematical form in Ref. [5], but allowing the single (control) parameter to span a fairly large range (which cannot be simply covered by a drop in amplitude), the steady states and differential (and weak) stabilities observed here can be captured by a gradient dynamics. That is, if, for instance, a potential is written as $V(\Delta\phi) = \varepsilon \cos \Delta\phi - \cos^2 \Delta\phi$, then a parameter range of $-4 \le \varepsilon \le 4$ yields both stable in-phase and antiphase coordination (see Fig. 3). For $\varepsilon = 0$ the potential becomes shallow and in-phase and antiphase are equally attractive yielding ongoing switches once random fluctuations are added. Incorporating detuning (i.e., an additional linear slope in the potential) can readily cause phase shifts but a mathematical treatment of this aspect is beyond the scope of the present article.

Hence, one may conclude that the general form of the dynamics of interlimb coordination also applies to walking side-by-side. Whereas for intrapersonal coordination several coupling components can be given that integrate as parameter ε, the link between persons walking side-by-side is more speculative. Indeed, as recognized by Zivotofsky and Hausdorff [23], increases in coupling strength may be achieved in a variety of ways, including the presence of sensory feedback (e.g., holding hands, walking on tapping shoes, walking on vibrating surfaces, etc.) and social factors (e.g., talking while walking, in-group versus out-group walkers, shared task goals, walking in a group, etc.). A definite position with regard to the applicability of a model of interpersonal coordination during walking like the one above should therefore await experimentation involving systematic manipulations of the prominence of relevant coupling factors as well as the difference in eigenfrequencies of the legs (i.e., by attaching masses). In all scenarios, however, the present data underscore the need to apply movement registration methods and time-resolved analysis techniques with a high degree of accuracy to bring out essential details of this delicate and intriguing form of interpersonal coordination.

References

[1] P.G. Amazeen, R.C. Schmidt, M.T. Turvey, Frequency detuning of the phase entrainment dynamics of visually coupled rhythmic movements, Biol. Cybern. 72 (1995) 511–518.
[2] J.J. Collins, I. Stewart, A group-theoretic approach to rings of coupled biological oscillators, Biol. Cybern. 71 (1994) 95–103.
[3] A. Daffertshofer, C. van den Berg, P.J. Beek, A dynamical model for mirror movements, Physica D 132 (1999) 243–266.
[4] A. Fuchs, V.K. Jirsa, H. Haken, J.A.S. Kelso, Extending the HKB model of coordinated movement to oscillators with different eigenfrequencies, Biol. Cybern. 74 (1996) 21–30.
[5] H. Haken, J.A.S. Kelso, H. Bunz, A theoretical model of phase transitions in human hand movements, Biol. Cybern. 51 (1985) 347–356.
[6] J.A.S. Kelso, On the oscillatory basis of movement, Bull. Psychon. Soc. 18 (1981) 63.
[7] J.A.S. Kelso, Phase transitions and critical behavior in human bimanual coordination, Am. J. Physiol. 246 (1984) 1000–1004.
[8] J.A.S. Kelso, J.J. Jeka, Symmetry breaking dynamics of human multilimb coordination, J. Exp. Psychol. Hum. Percept. Perform. 18 (1992) 645–668.
[9] J.A.S. Kelso, Dynamic Patterns: The Self-organization of Brain and Behavior, MIT Press, Cambridge, 1995.
[10] K.V. Mardia, P.E. Jupp, Directional Statistics, Wiley, Chichester, 2000.
[11] O. Oullier, G.C. de Guzman, K.J. Jantzen, J. Lagarde, J.A.S. Kelso, Social coordination dynamics: measuring human bonding, Soc. Neurosci., (2007), doi:10.1080/17470910701563392.
[12] A.S. Pikovsky, M. Rosenblum, J. Kurths, Synchronization, A Universal Concept in Nonlinear Sciences, Cambridge University Press, 2001.
[13] M.J. Richardson, K.L. Marsh, R.C. Schmidt, Effects of visual and verbal interaction on unintentional interpersonal coordination, J. Exp. Psychol. Hum. Percept. Perform. 31 (2005) 62–79.
[14] M.J. Richardson, K.L. Marsh, R. Isenhower, J. Goodman, R.C. Schmidt, Rocking together: dynamics of intentional and unintentional interpersonal coordination, Hum. Movement Sci. 26 (2007) 867–891.
[15] R.C. Schmidt, M.T. Turvey, Phase-entrainment dynamics of visually coupled rhythmic movements, Biol. Cybern. 70 (1994) 369–376.

[16] R.C. Schmidt, B. O'Brien, Evaluating the dynamics of unintended interpersonal coordination, Ecol. Psychol. 9 (1997) 189–206.

[17] R.C. Schmidt, C. Carello, M.T. Turvey, Phase transitions and critical fluctuations in the visual coordination of rhythmic movements between people, J. Exp. Psychol. Hum. Percept. Perform. 16 (1990) 227–247.

[18] R.C. Schmidt, M. Bienvenu, P.A. Fitzpatrick, P.G. Amazeen, A comparison of intra- and interpersonal interlimb coordination: coordination breakdowns and coupling strength, J. Exp. Psychol. Hum. Percept. Perform. 24 (1998) 884–900.

[19] J.H. Steiger, Tests for comparing elements of a correlation matrix, Psychol. Bull. 87 (1980) 245–251.

[20] J.J. Temprado, M. Laurent, Attentional load associated with performing and stabilizing a between-persons coordination of rhythmic limb movements, Acta Psychol. 115 (2004) 1–16.

[21] P.J. Treffner, M.T. Turvey, Handedness and the asymmetric dynamics of bimanual rhythmic coordination, J. Exp. Psychol. Hum. Percept. Perform. 21 (1995) 318–333.

[22] E.J. Williams, The comparison of regression variables, J. Roy. Stat. Soc. Ser. B: Stat. Met. 21 (1959) 396–399.

[23] A.Z. Zivotofsky, J.M. Hausdorff, The sensory feedback mechanisms enabling couples to walk synchronously: an initial investigation, J. Neuroeng. Rehabil. 4 (2007) 28.

Please cite this article in press as: N.R. van Ulzen, et al., Characteristics of instructed and uninstructed interpersonal coordination while walking side-by-side, Neurosci. Lett. (2008), doi:10.1016/j.neulet.2007.11.070