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Topological assessment of gait synchronisation in overground walking groups

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ABSTRACT

Walking is one of the fundamental forms of human gross motor activity in which spatiotemporal movement coordination can occur. While considerable body of evidence already exists on pedestrian movement coordination while walking in pairs, little is known about gait control while walking in more complex topological arrangements. To this end, this study provides some of the first evidence of spontaneous gait synchronisation while walking in a group. Nine subjects covered the total distance of 40 km at different speeds while assembled in a three-by-three formation. Two experimental protocols were applied in which the subjects were either not specifically asked to or specifically asked to synchronise their gait. To obtain results representative from the point of view of gait control, the movement coordination was quantified using the indirectly measured vertical component of ground reaction force, based on output from a network of wireless motion monitors. Bivariate phase difference analysis was conducted using wavelet transform, synchronisation strength measures derived from Shannon entropy, and circular statistics. A fundamental relationship describing the influence of the group walking speed on individuals' pacing frequency was established, showing a positive correlation different from that previously reported for walking in solitude. A positive correlation was found between the average synchronisation strength within a group and group's walking speed. The most persistent coordination patterns were identified for pedestrians walking front-to-back and side-by-side. Overall, the spontaneous gait synchronisation while walking in a group is relatively weak, well below the levels reported for walking in pairs.

1. Introduction

Persistent patterns of motor behaviour can emerge spontaneously within a pair of walking pedestrians, demonstrating that movements of one individual can be influenced by the actions of the other. This was previously shown for pairs walking either in side-by-side (Nessler & Gilliland, 2009; Nessler, Kephart, Cowell, & De Leone, 2011; Noy et al., 2017; Selmi, Bedira, Gharsallah, Gharbi, & Baudrand, 2010; Sylos-Labini, D'Avella, Lacquaniti, & Ivanenko, 2018; van Ulzen, Lamoth, Daffertshofer, Semin, & Beek, 2010; Zivotofsky, Bernad-Elazari, Grossman, & Hausdorff, 2018; Zivotofsky, Gruendlinger, & Hausdorff, 2012) or front-to-back (Harrison & Richardson, 2009; Marmelat, Delignières, Torre, Beek, & Daffertshofer, 2014) arrangements. However, very few studies have been conducted which could provide baseline information on spontaneous gait synchronisation in overground walking (Bocian et al.,

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2018; Harrison & Richardson, 2009; Pimentel, Araújo, Brito, & de Brito, 2013; Zivotofsky et al., 2012) while it is unlikely that the results of studies conducted on motorised treadmills with an imposed treadmill belt speed are representative of pedestrian behaviour in real-life conditions. This is because the pedestrian is then likely to overregulate their stride speed in comparison to overground walking (Dingwell & Cusumano, 2015) and be prevented from exercising fully adaptive stepping behaviour (Bocian, Burn, Macdonald, & Brownjohn, 2017). Furthermore, since the pedestrian is not moving relative to the environment, optic flow and motion parallax are in this case usually not preserved, while both are known to be used by walkers to stabilise their posture (Bardy, Warren, & Kay, 1996) and control spatial and temporal gait parameters (Wilkin, Cheryl, & Haddock, 2012), including speed (Patla, 1997).

It was previously shown that visual, auditory and proprioceptive systems can affect gait synchronisation for walking in pairs with the presence of cues from each of these modalities increasing the likelihood of synchronisation (Harrison & Richardson, 2009; Nessler & Gilliland, 2009; Noy et al., 2017; Sylos-Labini et al., 2018). However, little is known how the concurrent sensory information is integrated and used in the execution of gait while walking in groups, and how this can affect spontaneous gait synchronisation. While the proprioceptive system gives in this case unambiguous information of self-motion due to its endogenic origin, the information obtained from visual and auditory sensory modalities can be conflicting. This is because visual and auditory cues are exogenous in nature and can be independently generated by each pedestrian in the group assembly.

While the results obtained from pairs of pedestrians cannot be simply extrapolated to more complex topological arrangements, studies on pedestrians' gait coordination in overground walking groups and crowds are relatively rare (Bocian et al., 2018; Pimentel et al., 2013; Ricciardelli & Pansera, 2010). This can be attributed to the technological and logistical challenges pertinent to simultaneous data capture from multiple pedestrians over many gait cycles. Furthermore, there is no commonly adopted methodology for quantifying gait synchronisation, with previous studies using data of various origin (i.e. knee angle, head location, acceleration of lower back or neck) and adopting various signal processing techniques (i.e. detrended fluctuation analysis, Hilbert transform, continuous wavelet transform). Current evidence from a group of six pedestrians crossing a flexible footbridge, providing a mechanical coupling mechanism, suggests that the strength of interpersonal interactions depends on the spatial collocation within a group (Bocian et al., 2018). The interpersonal coupling mechanism is relatively weak with pedestrians having stronger tendency to coordinate their gait with structural motion rather than each other. In line with studies on pedestrian pairs (Nessler & Gilliland, 2009; Selmi et al., 2010; van Ulzen, Lamoth, Daffertshofer, Semin, & Beek, 2008) the front-to-back collocation yields the highest synchronisation strength, followed by the side-by-side collocation. However, walking is most often performed on a rigid ground and the information on gait synchronisation in a group specific for this case is currently unavailable.

Considering the above arguments, the aim of this study is to evaluate pedestrians' movement coordination while overground walking in a group. It was hypothesised that the availability of concurrent visual and auditory synchronisation cues from multiple pedestrians can cause the synchronisation patterns previously observed in pairs of walkers to break. To verify this postulate, a group of nine pedestrians arranged in a three-by-three formation walked along a straight outdoor pathway at different speeds while instrumented with wireless motion sensors. It was hypothesised that the instruction to synchronise steps or lack thereof can significantly affect gait synchronisation strength. It was also hypothesised that other determinants of gait synchronisation include the relative position of a pair of pedestrians within the walking formation, walking speed of the group, and height and mass difference.

2. Method

2.1. Participants

Nine healthy males in their twenties were recruited for the purpose of this study. Prior to the experiment, all participants were required to familiarise themselves with a participant's information letter, fill in a physical activity readiness questionnaire, and sign an informed consent form. The information regarding participants' weight and height is given in Table 1. Participants wore flat sole shoes and their own casual clothes adequate for typical British spring weather. The average temperature and wind speed on the testing day were 6.6 °C and 1.2 km/h.

The study was approved by the University of Leicester Ethics of Research Committee.

2.2. Location

A 100.8-meter-long straight outdoor pathway located within the premises of the main campus of the University of Leicester was chosen as a suitable experimental location. The location provided a clear and unobstructed line of sight throughout the entire pathway. As all of the tests were conducted on a Sunday morning, the location proved to be traffic-free and allowed for an

Table 1
Basic information about the participants of the experiment.

	Participant								
	1	2	3	4	5	6	7	8	9
Mass [kg]	75	98	90	70	59	53	65	79	66
Height [m]	1.88	1.75	1.88	1.93	1.65	1.65	1.65	1.91	1.80

undisrupted testing campaign.

2.3. Experimental protocol

Forty-four group tests and nine individual tests were undertaken in total.

During group tests participants walked in a straight line with different speeds while arranged in a three-by-three formation, i.e. organised in three rows and three columns. After each test, participants were rearranged in the formation to avoid any bias associated with collocation repetitiveness. To impose a walking speed, one extra person (a pacemaker) walked in front of the group of participants. Since the walking speed and pacing frequency are closely correlated (Bertram & Ruina, 2001), the walking speed of the group was controlled by setting the pacing frequency for the pacemaker via a hidden earpiece connect to a metronome. The pacemaker walked with pacing frequencies ranging from 1.3 Hz to 2.3 Hz, at 0.1 Hz increments. The order of frequencies was randomised to avoid any potential anticipatory behaviour. Each of the pacing frequencies was repeated four times but never in an immediate sequence. During the first thirty-three group tests, hereafter referred to as unintentional gait synchronisation experimental conditions and denoted US, at which each pacing frequency was repeated three times, the participants were only told to maintain the formation. For the final eleven group tests, hereafter referred to as intentional gait synchronisation experimental conditions and denoted IS, each of the set pacing frequencies was applied only once and the test subjects were instructed to walk in step.

The individual tests were carried out after all the group tests were finished. Each participant was requested to cover the pathway distance once at their preferred walking speed.

2.4. Instrumentation

Each of the test participants, except the pacemaker, had either APDM Opal™ or APDM Emerald™ wireless attitude and heading reference system (AHRS) attached at the back of their neck at the level of the seventh cervical vertebra (C7) with a medical-grade adhesive tape. The data recorded by the AHRS were time-locked and sampled at 128 Hz. For the purpose of this study, only the vertical component of the acceleration vector (i.e. aligned with the gravity vector) was used, obtained by resolving the recorded 3D acceleration signals from the local (i.e. sensor) to global coordinate system using the quaternion algebra. As shown in Bocian et al. (2016), the vertical acceleration signal resolved in this way, when multiplied by pedestrian mass, can provide a reasonable proxy of the vertical component of the ground reaction force (vGRF) both in terms of the amplitude and timing. Since ground reaction forces are fundamental to human locomotion as they serve to support and propel the body, the signal chosen for further analysis is also meaningful from the point of view of gait control, which is of primary interest in this study.

2.5. Data analysis

The pedestrian mass-normalised vGRF signals (i.e. vertical acceleration signals from C7 expressed in m/s^2) are the bases of all subsequent analyses presented in this study. These signals need to be processed further to obtain data suitable for the quantification of synchronisation strength and directionality. The directionality is understood here as the bias in the distribution of instantaneous phase difference, which may indicate there was a preferred mode of correlation of motion between a pair of pedestrians. The parameters pertaining to these gait qualities are obtained from the instantaneous pedestrian phase, providing information on the instantaneous point in the gait cycle. The mean walking speed was computed based on the known duration of the tests and the distance travelled (i.e. pathway's length).

2.5.1. Signal processing

Previous studies on synchronisation of gait used the analytic signal concept (Boccaletti, Kurths, Osipov, Valladares, & Zhou, 2002; Schelter, Winterhalder, Dahlhaus, Kurths, & Timmer, 2006; Zivotofsky et al., 2018). The analytic signal is constructed by applying Hilbert transform on the real-valued signal of interest. Since the analytic signal is represented on a complex plain, it contains information on the instantaneous amplitude and phase at all frequency components up to the Nyquist frequency (Smith, 2007). However, the problem with using this approach for instantaneous phase extraction is that it implicitly requires tight band-pass filtering around the frequency of interest. Considering the multi-modal nature of vGRF (or any other gait signals, for that matter), i.e. the spread of energy into harmonic components, including sub- and super-harmonics, this step can lead to the misinterpretation or even loss of some information. To address this problem, Bocian et al. (2018) proposed the use of a wavelet transform-based approach for the determination the instantaneous pedestrian phase from the walking gait data.

The wavelet-based approach relies on a bivariate (i.e. two at a time) analysis of correlation between signals. That was achieved by calculating the cross-wavelet transform. To allow for the separation of the amplitude and phase components within the signal, a complex wavelet function had to be used. The Morlet wavelet function was chosen due to its ability to capture the main characteristics of a human gait signal, in particular its multi-modal nature and smooth-varying amplitude. The wavelet scales were in the range of 1 to 256, linearly increasing by unity. The bandwidth parameter and the wavelet centre frequency were chosen as 1. The phase difference was obtained by calculating the arctangent between imaginary and real part of the complex cross-wavelet transform. The wavelet scale chosen to extract the phase difference was selected individually for each pedestrians' pair, such as to contain the largest cross-wavelet power. The first and last 5 s of the recorded signals were discarded to avoid gait initiation and termination stages.

2.5.2. Synchronisation quantification

To quantify the interaction between walking pedestrians a synchronisation strength index based on a bivariate (i.e. pairwise) analysis of the vGRF time-histories was employed. The index was first introduced by Tass et al. (1998) and it is based on Shannon entropy of phase difference distribution. The bivariate synchronisation strength index, ρ, can take values from 0 to 1, where 0 relates to a uniform distribution of phase difference, i.e. lack of synchronisation, whereas 1 corresponds to Dirac-like distribution of phase difference, i.e. perfect synchronisation.

2.5.3. Step-to-step variability in pacing frequency

Changes in step-to-step pacing frequency (hence step duration) could be a signature of gait adaptations. To obtain information on the variability of the timing of footsteps, a single-sided power-preserving magnitude of fast Fourier transform was calculated first for each vGRF signal to extract information about the average pacing frequency, f_p, of each participant. Next, the vGRF signal was filtered using forward and backward fourth-order band-pass Butterworth filter with edge frequencies of $0.5f_p$ and $1.5f_p$, thus ensuring no phase delay. Based on the location of the peaks of the filtered signal, the period T_p between consecutive steps was calculated. The pacing frequency f_p corresponding to each step was then obtained using the fundamental relation $f_p = 1/T_p$. A verification of the step identification algorithm was performed by filtering out those steps for which the pacing frequencies fell outside of the frequency range of the band-pass filter. For group tests, the total of 80 steps were disregarded through this process, which represents 0.15% of all steps detected. No steps were disregarded in the case of individual tests. It is worth noting that due to the nature of the vGRF signal no distinction is made in this study between steps taken with ipsi- and contra-lateral legs in the analysis of bivariate synchronisation index.

2.6. Statistical hypothesis testing

The Welch's *t*-test (Welch, 1947) at 5% significance level ($p = 0.05$) was first carried out on US and IS datasets to check whether the instruction to synchronise caused statistical difference in the synchronisation strength. Indeed, this was the most prominent factor. The first-order multiple linear regression analysis (Chambers & Hastie, 1992) was therefore performed on the US and IS datasets separately, adopting significance level of 5% ($p = 0.05$). The statistical model took the bivariate synchronisation strength as the dependent variable, whereas the explanatory variables were the distance between participants (defined as the magnitude of the planar vector connecting positions of participants in the formation, with the spacing between two consecutive rows or columns being equal to 1), walking speed, and height and mass difference available from Table 1. The quantities corresponding to the two group tests conditions, i.e. unintentional and intentional synchronisation, are hereafter denoted with superscripts US and IS, respectively.

3. Results

3.1. Statistical analysis

The walking speed of the group had a significant influence on the synchronisation strength for US and IS, but this relationship was stronger for IS, $t^{US} = 4.28$ and $p^{US} = 2.03\text{E}-05$; $t^{IS} = 5.24$ and $p^{IS} = 2.59\text{E}-07$. The height difference between participants had a strong influence on the synchronisation index for US only, $t^{US} = -11.20$ and $p^{US} < 2\text{E}-16$; $t^{IS} = -0.76$ and $p^{IS} = 0.45$. Similar influence was noted for the mass difference, $t^{US} = 2.00$ and $p^{US} = 4.55\text{E}-03$; $t^{IS} = -1.51$ and $p^{IS} = 1.31\text{E}-01$. Conversely, the distance between participants was influential only in the case of IS, $t^{US} = -0.87$ and $p^{US} = 0.38$; $t^{IS} = -4.94$ and $p^{IS} = 1.15\text{E}-06$. It may seem, based on the results from the statistical model aggregating all test-specific data and seeking global dependencies, that the group topology cannot explain the synchronisation strength in US. However, persistent local causalities in stepping behaviour between pedestrian pairs may still be present in this case. This will be investigated in Section 3.4.

3.2. Pacing frequency and walking speed

The relationship between the pacing frequency and walking speed for US and IS is shown in Fig. 1(a) and (b), respectively. The coefficient of determination (R^2) for the best linear fit for US and IS data is 0.65 and 0.97, respectively. The gradients of the fits are 0.66 and 0.87, and the intercepts are 0.99 and 0.63, for US and IS, respectively. The lower gradient of the fit for US indicates the adoption of a wider range of pacing frequencies for IS. The results from individual tests, denoted on the plots with circles, indicate the participants' preference towards the pacing frequencies and walking speeds at the top end of the respective ranges of these parameters observed for group walking.

The relationship between the coefficient of variation (CoV) of the pacing frequency and walking speed for US and IS is shown in Fig. 2(a) and (b), respectively. The best fit second-degree polynomials shown for data from the group tests have R^2 values of 0.16 and 0.39 indicating a large spread of data around the fitted curves. The data from individual tests, denoted on the plots with circles, generally fall below the data from group tests at a given walking speed and the best fit to these data is linear. The average values of CoV of pacing frequency are higher for the IS and all reduce with the walking speed, bearing in mind the best polynomial fit in Fig. 2(a) is extrapolated beyond the walking speed of 1.5 m/s hence may only be indicative of true behaviour.

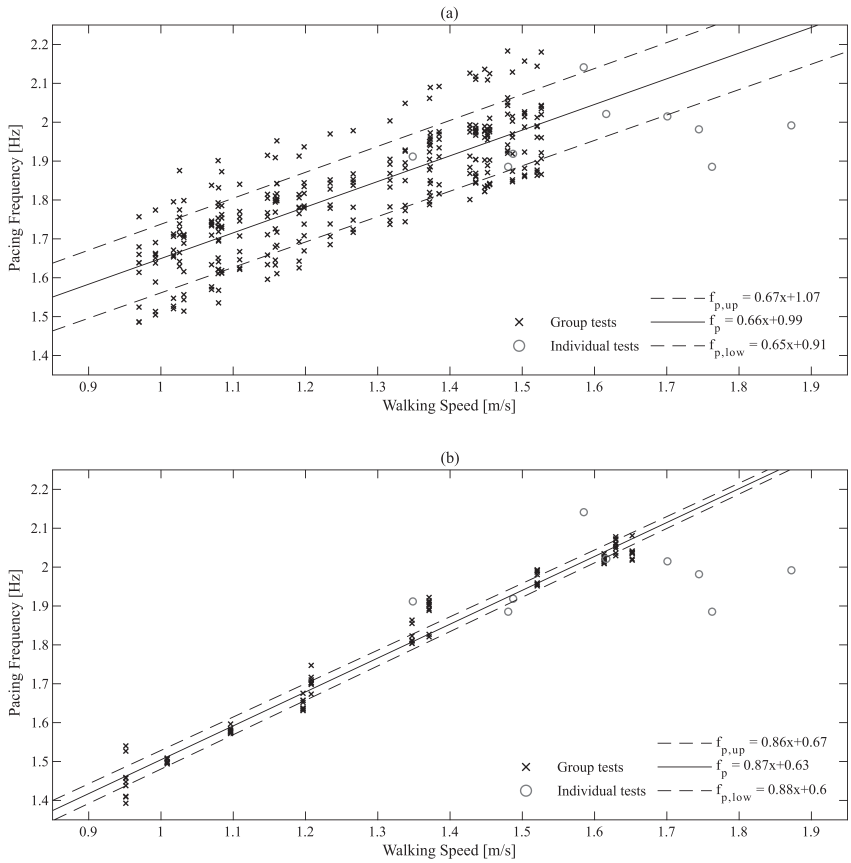

Fig. 1. Pacing frequency as a function of the walking speed for (a) US and (b) IS tests. Best linear fits are given with one standard deviation band.

3.3. Synchronisation strength

To gain an insight into general dependencies between pedestrians walking in a group, which might be independent of the walking speed, and enable a direct comparison of synchronisation strength between the US and IS, synchronisation indices were averaged across all tests within the respective test type. The results are shown in Fig. 3. The highest average synchronisation indices were always obtained for the direct connections, i.e. where there is an unobstructed line of sight between the pedestrians. The highest average synchronisation index for US and IS was obtained for the pair $P_{1,4}$ ($\rho_{1,4}^{US} = 0.051$) and $P_{1,2}$ ($\rho_{1,2}^{IS} = 0.307$), respectively, where the numbers in subscript denote the pedestrian locations as shown in Fig. 3.

Considering all tests and collocations between pedestrians within the walking formation separately, the maximum synchronisation strength index for IS was higher than that for US, $\rho_{\max}^{IS} = 0.618$ and $\rho_{\max}^{US} = 0.409$. The mean synchronisation strength was also significantly higher for IS, $\bar{\rho}^{IS} = 0.179$ and $\bar{\rho}^{US} = 0.032$, where dash over the symbol denotes the mean value. However, the relative variation of synchronisation indices was much higher for US, which is represented by the CoV of 186% and 69% for US and IS, respectively.

The average values of the synchronisation strength index for all US and IS tests and their dependence on the walking speed are shown in Fig. 4(a) and (b), respectively. The best linear fits to US and IS data are characterised by R^2 of 0.49 and 0.21, respectively. For both test types, the average synchronisation strength index is likely to increase with the walking speed.

To further generalise the results from all tests, observer-centred topological interaction maps were created by grouping and averaging bivariate synchronisation indices from those connections which shared the same spatial characteristics. For example, in a three-by-three formation applied during the tests there are eight direct diagonal connections (i.e. participants located in the immediately neighbouring row and column within the walking formation) and six direct shoulder-to-shoulder connections (i.e. participant located side-by-side). The results are presented in Fig. 5. The highest synchronisation strength for US is visible in Fig. 5(a) for the direct front-to-back connection, hereafter denoted $C_{1,0}$. According to this notation convention, the first and second number in the subscript indicate, respectively, the numbers of rows and columns separating the participants. The synchronisation strength for all other connections in Fig. 5(a) falls below 0.04. Similarly, the highest synchronisation strength for IS is visible in Fig. 5(b) for $C_{1,0}^{IS}$, at 0.249. This is followed by the direct side-by-side connection, $C_{0,1}^{IS}$, at 0.201. The synchronisation strength for all other connections in Fig. 5(b) falls below 0.2, which was previously suggested to signify the threshold separating unsynchronised and synchronised states in pairs of walking pedestrians (Zivotofsky et al., 2012).

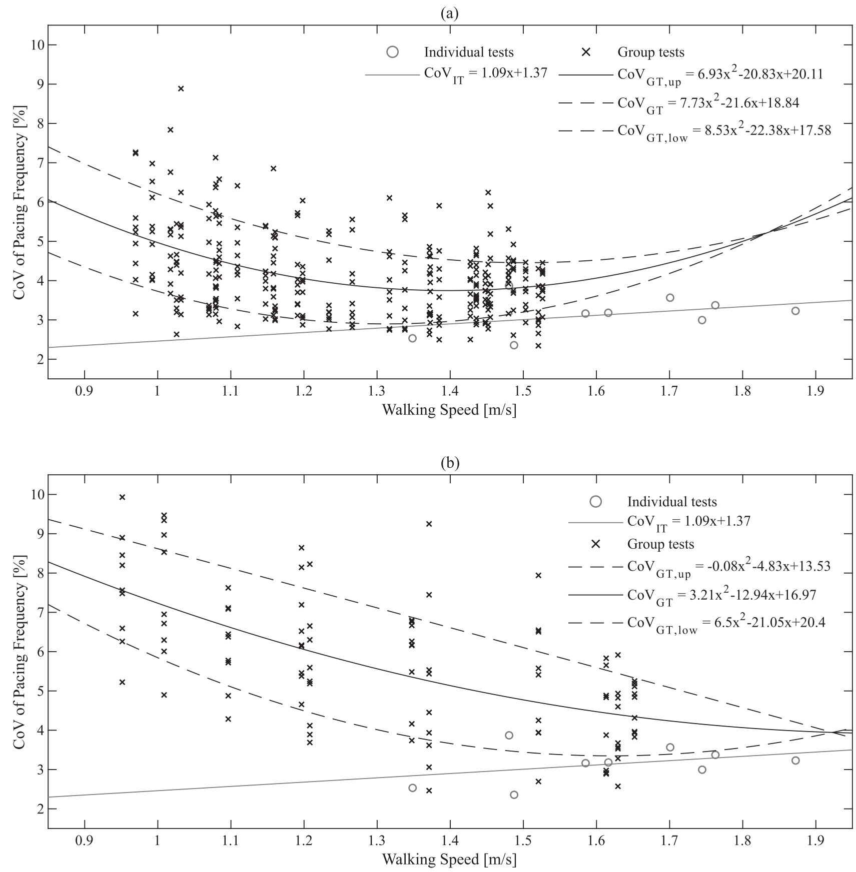

Fig. 2. Coefficient of variation of the pacing frequency as a function of the walking speed for (a) US and (b) IS tests. Best fit second-degree polynomials are given with one standard deviation band.

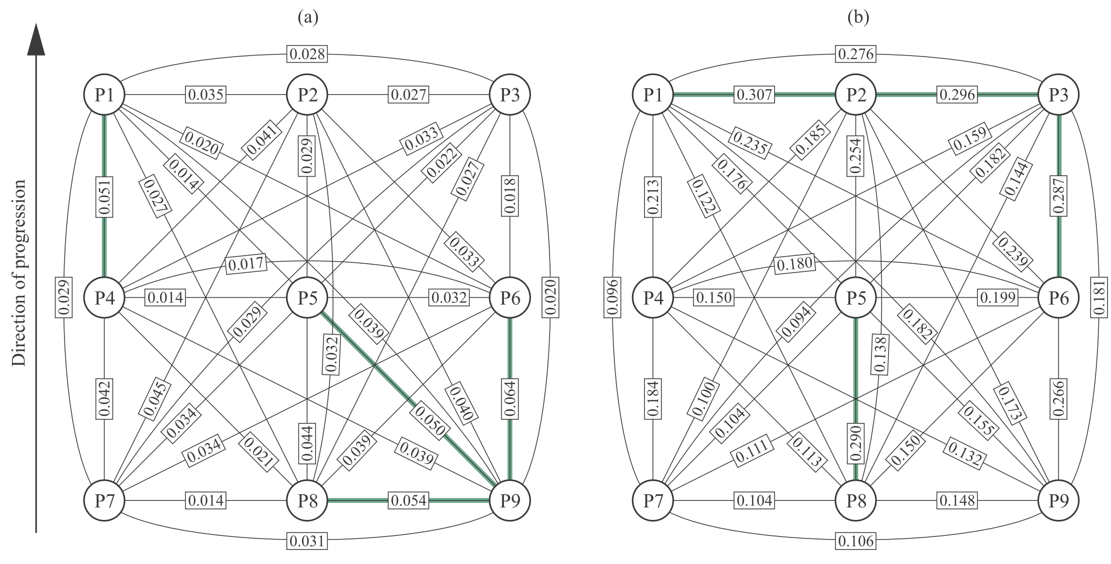

Fig. 3. Position-oriented interaction map with the average synchronisation strength indices for (a) US and (b) IS tests.

3.4. Interaction directionality

In the absence of other synchronisation stimuli, e.g. tactile feedback from holding hands and mechanical coupling by the motion of the walking surface, and considering the abundance of auditory cues due to the presence of multiple pedestrians within the

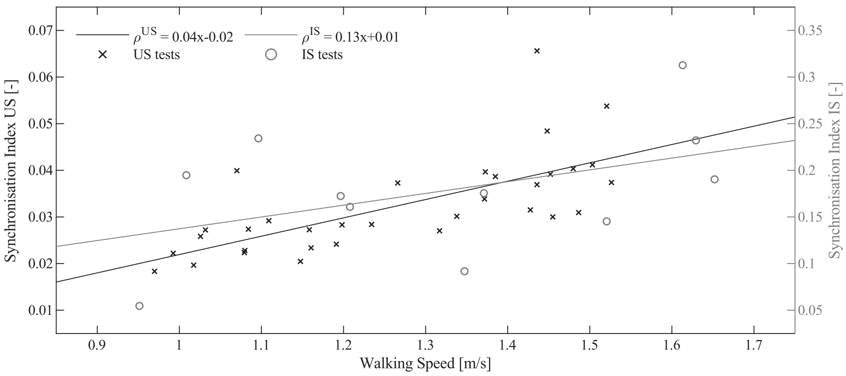

Fig. 4. The average group synchronisation strength index as a function of the walking speed for (a) US and (b) IS tests, together with best linear fits.

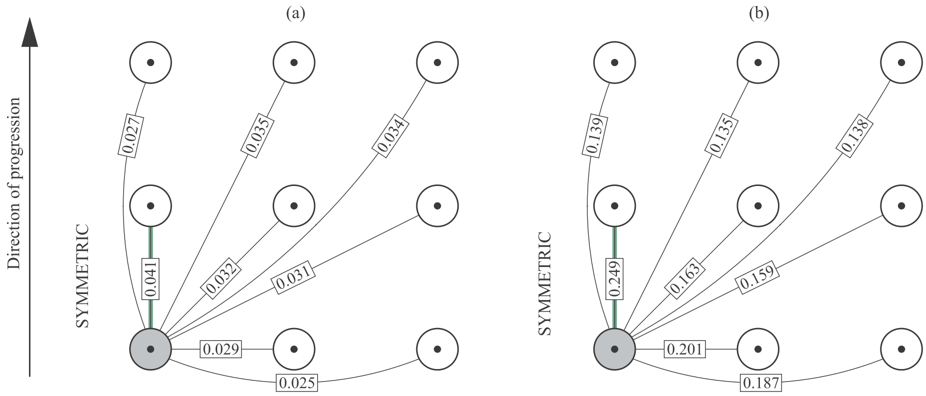

Fig. 5. Observer-centred topological interaction map with averaged synchronisation strength indices for (a) US and (b) IS tests.

walking formation, it can be assumed that visual system may provide information promoting gait synchronisation. In most cases, the convention for quantifying the directionality is not an ambiguous problem as one pedestrian from the considered pair is in the other pedestrian's field of view, but the opposite is not true. Let us take the direct front-to-back connection (i.e. participants are located in the immediately neighbouring rows within the walking formation) for IS as an example, for which the synchronisation strength index is 0.249. It can be assumed that any adaptive stepping behaviour within this pedestrian pair was in this case exhibited by the follower, i.e. the pedestrian walking behind the other. This is because humans' field of view (FoV) spans approximately 200 and 135 degrees in horizontal and vertical plane (Howell, 1960), respectively, hence the leader, i.e. the pedestrian walking in front, is unlikely to maintain a line of sight with the follower. The same assumption holds for all diagonal connections. The only obvious exemption is the side-by-side connection, where both participants were in each other's FoV. It needs to be pointed out that for the front-to-back and side-by-side connections where the line of sight was obstructed by another participant, the argument of the influence of visual information on synchronisation may not hold. Nevertheless, to address this issue and assess the directionality in motion coordination, phase difference distributions were examined considering all collocations of the pedestrian pairs. If the phase difference is predominantly accumulated at the centre of a histogram ($\varphi = 0$), then even though the two pedestrians had a tendency to synchronise their gait, neither of them was more dominant, i.e. influencing the behaviour of the other pedestrian. If the phase difference, described within a range between $-\pi$ and π, was predominantly positive or negative, one of the pedestrians was likely to be either influencing or influenced by the other, respectively. Although this assertion is true in the mathematical sense, it needs to be borne in mind that the bivariate phase difference analysis cannot unequivocally distinguish whether the observed relationship was caused by the interactions between the considered pair of pedestrians, or interactions with other pedestrians within the group assembly. Nevertheless, given a sufficiently large dataset, the analysis using this method should uncover any persistent synchronisation patterns in the network topology.

The detailed statistical measures of the phase difference distributions for US and IS, including the mean circular direction of the phase difference $\bar{r}$, the mean resultant vector length R, circular deviation S, kurtosis k and the skewness d are presented in Table 2 (Berens, 2009). The mean circular direction $\bar{r}$ was calculated by transforming all phase difference values into a two-dimensional vector $r_i = (\cos\alpha_1, \sin\beta_2)$ and averaging over the number of data points. The mean resultant vector length R is a quantity that measures the spread of the data. The values closer to 0 indicate a large spread of data points, and values in proximity to 1 indicate a condensation of data points around the circular mean (Berens, 2009). To check for the uniformity of the phase difference distribution, the Rayleigh and Omnibus tests were applied to the data, adopting the null hypothesis that the phase difference population is distributed uniformly around the circle and 5% significance level $p = 0.05$ (Zar, 2010). Both tests rejected the hypothesis for all

Table 2
Measures of circular statistics of phase difference for all connections.

Connection	Number of occurrences	Experimental conditions	Sync strength index ρ	Mean circular direction φ	Mean resultant vector length R	Circular deviation S	Kurtosis k	Skewness b
$C_{0,1}$	198	US	0.0293	−0.4188	0.0122	1.4055	0.0020	0.0036
$C_{0,1}$	66	IS	0.2005	0.1069	0.2608	1.2159	0.0632	−0.0072
$C_{0,2}$	99	US	0.0252	−1.3327	0.0321	1.3913	−0.0011	−0.0076
$C_{0,2}$	33	IS	0.1872	0.0619	0.2715	1.2070	0.0238	−0.0293
$C_{1,0}$	198	US	0.0413	0.2703	0.0405	1.3853	0.0183	−0.0126
$C_{1,0}$	66	IS	0.2489	0.5068	0.4423	1.0561	0.0898	−0.0064
$C_{1,1}$	264	US	0.0317	1.1451	0.0206	1.3995	0.0053	−0.0021
$C_{1,1}$	88	IS	0.1630	0.3668	0.2330	1.2386	0.0621	0.0196
$C_{1,2}$	132	US	0.0315	1.7374	0.0403	1.3854	0.0006	−0.0098
$C_{1,2}$	44	IS	0.1590	0.2652	0.2274	1.2431	0.0175	−0.0172
$C_{2,0}$	99	US	0.0270	−1.8587	0.0194	1.4005	0.0074	−0.0031
$C_{2,0}$	33	IS	0.1387	0.7195	0.1383	1.3128	−0.0241	−0.0513
$C_{2,1}$	132	US	0.0346	−0.2884	0.0117	1.4059	0.0037	−0.0127
$C_{2,1}$	44	IS	0.1346	0.6313	0.2041	1.2617	−0.0139	−0.0476
$C_{2,2}$	66	US	0.0341	1.6657	0.0128	1.4051	−0.0044	−0.0054
$C_{2,2}$	22	IS	0.1380	0.1702	0.1805	1.2802	0.0502	−0.0053

connections.

Fig. 6 shows histograms of the phase difference distribution for the direct front-to-back and the side-by-side connections, i.e. $C_{1,0}$ and $C_{0,1}$, respectively, for US and IS. For US, the phase difference for $C_{1,0}^{US}$ and $C_{0,1}^{US}$ is almost uniformly distributed around the circle, having the mean circular direction close to 0, i.e. $\bar{r}_{0,1}^{US} = -0.42$ rad and $\bar{r}_{1,0}^{US} = 0.27$ rad. The values of the mean resultant vector length

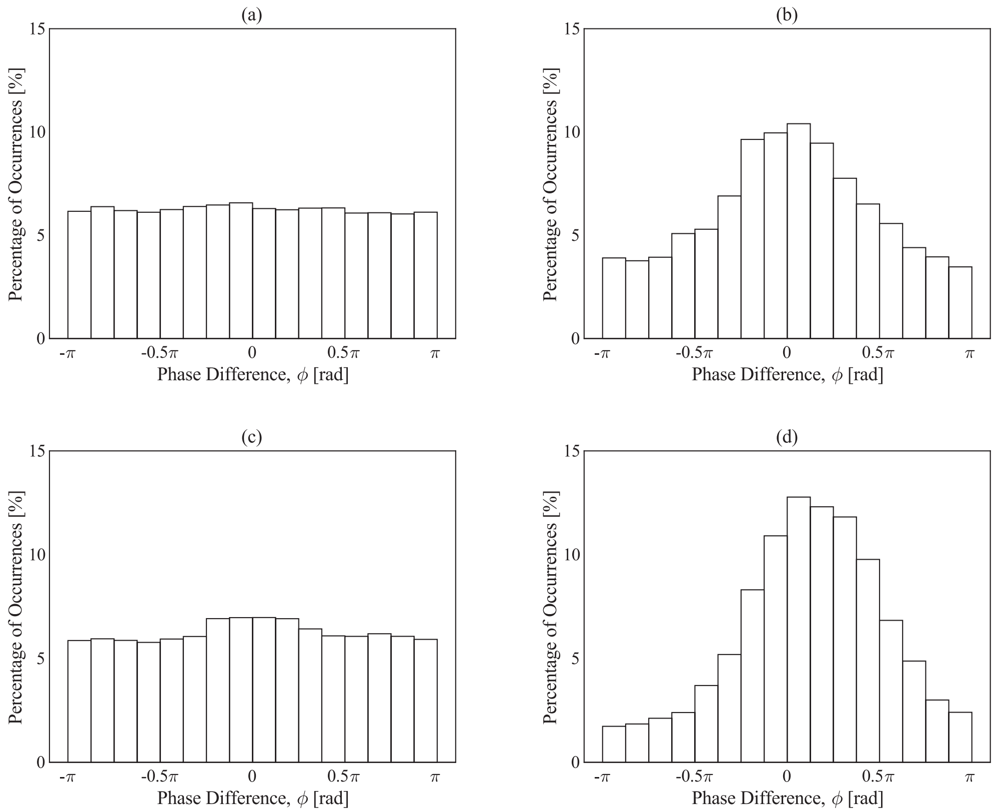

Fig. 6. Phase difference distribution for (a) side-by-side connection $C_{0,1}$ under US experimental conditions, (b) side-by-side connection $C_{0,1}$ under IS experimental conditions, (c) front-to-back connection $C_{1,0}$ under US experimental conditions and (d) front-to-back connection $C_{1,0}$ under IS experimental conditions.

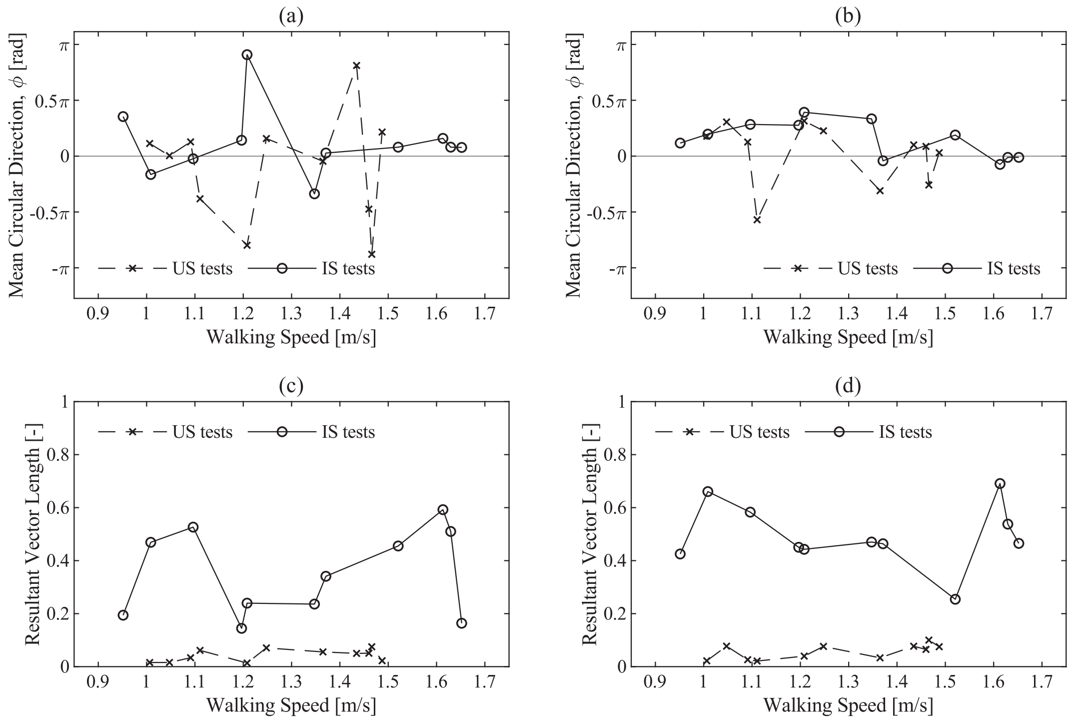

Fig. 7. The mean circular direction for side-by-side connection $C_{0,1}$ (a), the mean circular direction for front-to-back connection $C_{1,0}$ (b), the mean resultant vector length for side-by-side connection $C_{0,1}$ (c) and the mean resultant vector length for front-to-back connection $C_{1,0}$ (d).

are $R_{0,1}^{US} = 0.01$ and $R_{1,0}^{U} = 0.04$, signifying a relatively small accumulation of phase difference around the centre of the histogram. On the other hand, the phase difference histograms for IS take almost a bell-like shape, with the mean circular direction of $\bar{r}_{0,1}^{IS} = 0.11$ rad and $\bar{r}_{1,0}^{IS} = 0.51$ rad. The mean resultant vector lengths are $R_{0,1}^{IS} = 0.26$ and $R_{1,0}^{IS} = 0.44$. Both histograms show strong bias in the phase difference distribution, with the histogram for $C_{1,0}^{IS}$ clearly showing the front-to-back directionality of the synchronisation (i.e. the front pedestrian influencing the stepping behaviour of the back pedestrian), and the histogram for $C_{0,1}^{\mathrm{IS}}$ being inconclusive on the matter of the synchronisation directionality.

The mean circular direction and the resultant vector length over the range of walking speeds for connections $C_{1,0}$ and $C_{0,1}$ are shown in Fig. 7. No clear trend is visible in Fig. 7(a) and (b) for all but $C_{1,0}^{\mathrm{IS}}$ connection for which the mean circular direction takes predominantly positive values, indicating the front pedestrian was influencing the stepping behaviour of the back pedestrian. The mean resultant vector length is persistently higher for IS rather than for US in Fig. 7(c) and (d). Neither dataset presented in Fig. 7 shows a convincing dependency on the walking speed.

3.5. Height difference

The pedestrian height is closely related to the leg length. Previous studies on interpersonal synchronisation of gait (Nessler & Gilliland, 2009) showed that the likelihood of synchronisation increases with the decrease in the magnitude of leg length difference between pairs of subjects walking side-by-side. To assess whether this relationship also holds in the case of walking in a group, for each of the thirty-six pairwise connections, the absolute value of the height difference and average synchronisation strength index from thirty-three tests conducted under US experimental conditions were computed. The results are shown in Fig. 8. The results for IS were not considered in this assessment as it may be expected that the intentional synchronisation could have overwritten any naturally occurring synchronisation tendencies and causalities underlying this phenomenon. Nevertheless, for completeness, these results are also shown in Fig. 8. For low values of the synchronisation strength index $\rho \leq 0.03$, the data points seem to be randomly distributed in Fig. 8. However, with the increase of the synchronisation strength index, the magnitude of height difference diminishes, which is consistent with the results obtained in Bocian et al. (2018). The functional relationship between the synchronisation strength and the modulus of height difference is indicated in Fig. 8 as a power law. The spread of the data around the fit is rather large, with R^2 of 0.25.

4. Discussion

Previous studies classified gait coordination by proposing a threshold separating synchronised and unsynchronised states (Zivotofsky et al., 2012) or considered in-phase and in-antiphase locking when accompanied by frequency locking as the only

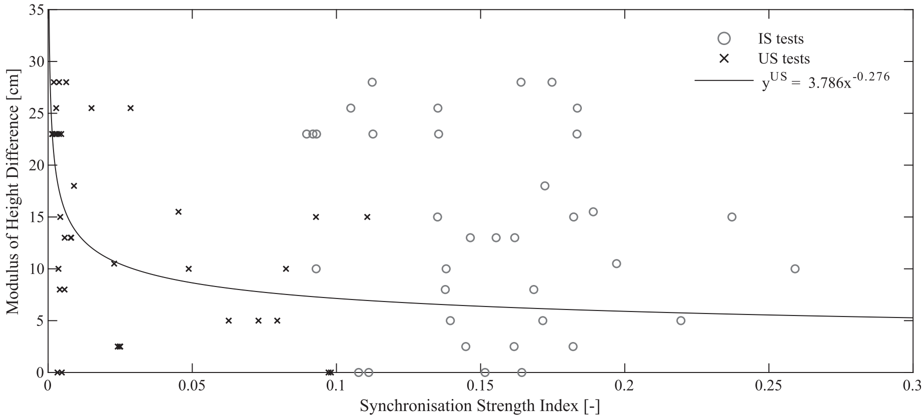

Fig. 8. The modulus of the height difference versus the average synchronisation strength index for US and IS tests, together with the best fit power function.

meaningful conditions for phase difference analysis (Nessler & Gilliland, 2009). However, recent experimental findings suggest that pedestrian's gait coordination when walking in a group (Bocian et al., 2018) and on an oscillating treadmill (Bocian et al., 2017; Nessler, Heredia, Belair, & Milton, 2017) can be more intricate, escaping typological divisions resulting from these definitions. Therefore, a more liberal approach was adopted in this study by analysing the bias in phase difference distribution but without imposing any classifiers, instead relying on the volume of data to reveal any persistent motion coordination patterns and ensure statistical power of the results. A total distance of close to 41 km was covered by the participants during the study, yielding 54,554 steps.

4.1. Walking speed – pacing frequency relationships

An increase of the walking speed results in an increase of the pacing frequency for individuals walking in real-life settings (Grieve & Gear, 1966; Pachi & Ji, 2005) as well as on a treadmill (Cotes & Meade, 1960; Dang & Živanović, 2015; Dean, 1965; Workman & Armstrong, 1963). The presented results for US tests concur in this respect, suggesting a linear relationship between these gait variables (Fig. 1(a)). This is similar to the findings in Dang and Živanović (2015) for individual pedestrians walking on a treadmill in a laboratory environment. Although this relationship was described using a quadratic function in that study, its shape in the range of the measured group walking speeds is very close to linear ($R^2 = 0.999$). However, the rate at which the pacing frequency increases with the walking speed is lower for US tests by 7%. The cause of this discrepancy can be twofold. Firstly, walking on a treadmill can cause statistically significant differences in temporal and spatial gait variables in comparison to overground walking, in particular decreased step time, increased pacing frequency and decreased step length (Alton, Baldey, Caplan, & Morrissey, 1998; Stolze et al., 1997). Secondly, it can be a consequence of the gait adaptation strategies while walking in a group. The results from the individual tests conducted for the purpose of this study fall within approximately one standard deviation from the linear fit for the US group tests (Fig. 1(a)), suggesting this relationship is applicable generally for the cohort of participants. However, these values are either at the top end or well beyond the highest values observed for group walking, indicating the adaptive nature of human stepping behaviour in the presence of multiple pedestrians.

The slope of the linear fit to the results from IS tests (Fig. 1(b)) is significantly steeper than that for US tests, with some results from the individual tests falling far beyond the boundary of two standard deviations. This indicates that intentional synchronisation forces the gait to operate within a different dynamic regime.

4.2. Gait variability

The adaptive stepping behaviour exercised by pedestrians while walking in a group increases the variability of gait parameters in comparison to walking in solitude (Fig. 2). The gait variability is speed-dependent, as could be expected from the results of studies probing this relationship for individual walkers (Chien, Yentes, Stergiou, & Siu, 2015; Jordan, Challis, & Newell, 2007; Kang & Dingwell, 2008). The gait variability generally decreases with the increase in the walking speed for IS tests. For US tests, the lowest variability is found at the range of walking speeds between 1.3 and 1.4 m/s, which corresponds to the average speeds observed for pedestrians walking on shopping floors and footbridges (Pachi & Ji, 2005). The human gait at this range of walking speeds is associated with minimum energy expenditure, increased stability and minimum control demands (Wilkin et al., 2012).

It needs to be pointed out that, in most cases, the speed chosen by participants during individual walking tests was higher than those achieved during group tests. As could be expected, the values of CoV for the pacing frequency for the IS tests (Fig. 2(b)) are greater than those from US tests (Fig. 2(a)), which reflects the need of constant gait adaptation to fulfil the requirements of the imposed cognitive task during IS tests.

4.3. Walking speed – synchronisation strength relationships

An increase of the average synchronisation strength within the pedestrian group was observed with the increase of the walking speed (Fig. 4), which may be associated with the amount of space available in front of the walkers. For a pedestrian to walk freely, i.e. without having to adjust their stepping behaviour due to the proximity of fellow walkers, some minimum space is required. In the case unobstructed stepping behaviour is not facilitated, the steps taken are often shorter to prevent from collisions and ensure some margin of comfort. This additional gait control requirement may break the synchronisation patterns occurring in free walking. The analysis of the video footage from the experiments showed that the average spacing between rows of participants was less than 1 m for the slowest walking speeds and steadily grew up to 1.8 m for the fastest walking speeds. According to the results from Dang and Zivanovic (2015) obtained for walking on a treadmill, the average step length, defined as the longitudinal distance the pedestrian heel travels between two consecutive heel strikes should increase from 0.6 m to 0.75 m with the increase of the walking speed from 1.1 to 1.7 m/s. The space available in front of the pedestrians for the lowest walking speeds was less than 1.7 of their desired step lengths, whereas for the fastest walking speeds that space grew to 2.4 of their desired step lengths. Greater space availability allowed participants to fully exercise gait adaptability as they were able to achieve a wider range of gait parameters. This, in turn, encouraged gait synchronisation.

4.4. Synchronisation strength for different pedestrians' collocations

Observer-centred topological interaction maps under US and IS conditions (Fig. 5) show that the direct front-to-back connection exhibits the highest synchronisation strength index, which is in-line with previous findings for group walking (Bocian et al., 2018). It was evident in that study that, at a slow walking speed, the pedestrian positioned at the back was most often taking a step slightly faster than the pedestrian in front. This was explained by an anticipatory behaviour associated with the collision avoidance (Repp & Su, 2013). According to this notion, the pedestrian in the back will try to arrive to the double stance phase of gait slightly faster than the pedestrian in front. This is because this phase of gait is more stable and enables collision avoidance corrections to be implemented more easily than in the single stance phase. The current study was not able to support this argument as for all US tests the phase difference distribution had a mean circular direction close to zero and a small value of mean resultant vector length (Table 2). However, the experimental campaign carried out by Bocian et al. (2018) was different to that in this study in that the tests were performed on a vibrating footbridge which provided a tactile feedback and acted as a mechanical coupling mechanism.

The average synchronisation strength indices for US are significantly lower than those obtained for unaccompanied pairs of pedestrians walking in front-to-back or side-by-side arrangements while exposed to different combinations of visual, auditory and mechanical synchronisation cues (Harrison & Richardson, 2009; Nessler & Gilliland, 2009; Nessler et al., 2011; Noy et al., 2017; Selmi et al., 2010; Sylos-Labini et al., 2018; van Ulzen et al., 2008, 2010; Yang, Wang, & Hu, 2016; Zivotofsky et al., 2012, 2018). In fact, even the average synchronisation strength obtained from IS tests is only 0.18, which is below the threshold previously proposed to mark the boundary separating synchronised and unsynchronised states for unintentional synchronisation while walking in pairs (Zivotofsky et al., 2012). The weakening of gait coordination patterns in group walking can be associated with the availability of concurrent sensory stimuli from multiple pedestrians.

In the case of the IS, the front pedestrian was, on average, taking their step faster that the back pedestrian. This can be explained by dynamic gait adaptation of back pedestrian based on visual and auditory cues provided by the front pedestrian, which was also postulated by Harrison and Richardson (2009) and Marmelat et al. (2014). When considering walking conditions without the presence of any external sensory feedback which can increase synchronisation, e.g. talking or hand-holding, the front-to-back connection seems to be of greater relevance in crowd behaviour than the side-by-side connection. This is because it is the only connection always present during dynamic lane formation in crowd counter-flow (Hoogendoorn & Daamen, 2003; Kretz, Grünebohm, Kaufman, Mazur, & Schreckenberg, 2006; Zhang, Klingsch, Schadschneider, & Seyfried, 2012).

The side-by-side connection showed the second highest synchronisation strength for IS tests but only sixth highest for US tests (Fig. 5). This can be assigned to the attention tuning. During US tests, the only participants' goal was to reach the end of the testing pathway while preserving the group cohesion. An additional requirement imposed during IS tests was adjusting the stepping behaviour to the neighbouring pedestrians. The side-by-side connection, being one of the three direct connections (the diagonal connection $C_{1,1}$ is also a direct connection since the pair of pedestrians is not separated by others), provided a strong synchronisation cue and became a part of participants' attention focus.

4.5. Gait optimisation

The optimisation of energy expenditure was suggested as a mechanism that plays a part in increasing the probability of gait synchronisation for pairs of pedestrians with a similar height (Bocian et al., 2018; Nessler & Gilliland, 2009). Since the height is strongly correlated with the leg length, these pairs of pedestrians are most likely to have the lowest metabolic cost of walking at similar pacing frequencies at a given walking speed (Bereket, 2005; Cavagna & Franzetti, 1986; Holt et al., 1990; Kuo, 2001). Only small adjustment in gait parameters, if any, are in this case needed to achieve some degree of synchronisation. Conversely, a pair of pedestrians with a significant height difference is less likely to synchronise their gait as this would require for at least one of them to change their gait parameters away from the biomechanical optimum. This phenomenological explanation can be easily expressed in the language of dynamical systems theory; there is a point at which the energy considerations overcome the weak attractor causing the pedestrians to walk in step. This point marks the limit at which the pedestrians break any motion correlation and essentially act as uncoupled oscillators. This applies in the absence of other constraints which could affect the group dynamics. To test this and other explanatory mechanisms of interpersonal synchronisation, further work will investigate various models suggested capable of capturing interaction dynamics in walking (Almurad, Roume, & Delignières, 2017; Roume et al., 2018).

5. Conclusions

Overground walking in a group causes task-specific adaptive patterns in pedestrian stepping behaviour. This manifests in an altered fundamental relationship between walking speed and pacing frequency from that previously reported for walking in solitude, and gait synchronisation patterns different from those previously reported for walking in pairs.

The variability of the pacing frequency, reflecting gait control, for tests with participants not specifically asked to synchronise their gait (herein referred to as unintentional synchronisation, denoted by US) is the lowest at the speed of approximately 1.4 m/s. This falls within the range of preferred speeds observed for pedestrians walking in real-life settings and corresponds to the speeds reported as optimal from the point of view of energy expenditure and gait stability. The instruction to synchronise steps (herein referred to as intentional synchronisation, denoted by IS) causes pedestrians to operate in a different dynamic regime, away from that observed for US.

The spontaneous gait synchronisation (in US) is generally weak and determined by the biomechanical similarity between pedestrians rather than the overall group topology. However, the front-to-back pedestrian collocation persistently yields the highest synchronisation strength index for US and IS, followed by side-by-side collocation for IS.

The average synchronisation strength is lower for IS in groups than the threshold delimiting spontaneous synchronisation previously proposed for pairs of pedestrians, set at 0.2. The only cases where this threshold is exceeded are the front-to-back and side-by-side connections in IS, at 0.249 and 0.201, respectively, suggesting the presence of concurrent visual and auditory information from multiple pedestrians may prevent high levels of movement coordination.

A positive correlation between the average synchronisation strength of a group and the walking speed is identified which is more pronounced for US. This can be associated with the decrease of the group density with the increase of the walking speed, resulting in the increase of the space available around each walker. This in turn enables a full range of adaptive stepping behaviours to be exercised, some of which may promote synchronisation, in the decrement of the requirement for collision avoidance manoeuvres which are prevalent at lower walking speeds.

The phase difference between pedestrians walking in a group seems generally random and independent of the walking speed. This is apart from the pedestrian connections yielding the highest synchronisation strength for which the phase difference usually takes values at and around zero, indicating in-step synchronisation, bearing in mind no distinction is made in this study between steps taken with ipsi- and contra-lateral legs.

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