Timing and distance characteristics of interpersonal coordination during locomotion

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Abstract

Most studies about human locomotion only tend to consider single subjects walking alone in a stationary environment. Nevertheless, human subjects have often to plan and generate their locomotor trajectories according to one another’s displacements. Therefore, in the present study we address the question of the interpersonal coordination when pairs of subjects walk simultaneously. Six pairs of subjects walking face to face, backwards and forwards on a 8 m × 2 m track were involved in our experiment. Within each pair, the leader (L) was required to break the initial interpersonal distance whereas the follower (F) had to maintain this distance constant (1, 2 or 3 m). We measured their position and analyzed their travelled distance, the time course of their linear displacement, and the kinematics parameters of their steps. Our results show that F travels smaller distances than L and that even if they are highly correlated, some temporal delays exist between displacements of L and F with greater values when the interpersonal distance increases (from 1 to 3 m). These results are discussed in terms of high level imitation, i.e. bidirectional interactions with mutual influences of each subject on one another.

Keywords: Locomotion; Interpersonal distance; Coordination; Imitation; Leadership; Human

Locomotion is a complex neural process, involving central programs and afferent inputs [6,7], which is used by human subjects to displace their entire body from one place to another in the environment [18]. Producing coordinated segmental movements of the lower [2,3,5] and upper limbs, as well as the head and trunk to perform such tasks provides the CNS with information of peripheral origin about the state changes of one’s own body during the displacement. Furthermore, stabilizing the head in space constitutes an effective strategy to get a reliable frame of reference for navigation, to maintain the walking direction [19,20] or to control the repositioning of the body in space when direction changes are needed [10,13,14]. Even if locomotion involves a rhythmic segmental activity, the locomotor pattern results from the cognitive intention of the subject to reach or move away from a spatially located goal, to avoid obstacles or to follow a path. Therefore, the brain must not only encode different pieces of information about the surrounding space as well as the state of the displaced body and its actual position in space, but must compare also this information to representations of the potential paths to a goal. Moreover, the difference between the actual trajectory and the intended centrally planned trajectory must be evaluated. It has been shown recently that the geometry of the path to be followed can be internalized and that a purely cognitive activity such as mental simulation contributes to improve navigation performance without vision [26].

Most studies assume the necessity for the CNS to merge information arising from the body itself and the environment during a locomotor activity. But they tend to consider single subjects only moving alone toward a previously seen target
with difficulty and may lead to an embarrassing feeling\[1\].

Within this space, the presence of others is tolerated that people tried to maintain a personal space around them-

\[1\] about interpersonal distance, proxemic studies showed that the timing and interpersonal distance may depend both

on the role played by each subject within the pair in terms of leadership and on the amount of space they try to maintain

the present study is to characterize the interaction between

locomotor trajectories according to another person’s dis-

placements. For instance, this may be the case when two

people walking in the street want to cross over and shake

hands, when making one’s way through the crowd or when

one plays team sports (e.g. basketball, rugby) or direct oppo-

sition sports (e.g. fencing, boxing). During a preparation

phase, both fencers control the distance between them by a

footwork. When one of them feels to be close enough to

reach the other one, he makes an attack movement. For

each displacement, either offensive or defensive, fencers

have their own preferential distance. Experience tells us that these distances can be modulated by the opponent’s

behaviour. This opponent may be considered as a moving

landmark and thus alter the geometrical features of the envi-

ronment.

Despite the theoretical and practical importance of this

question, the motor coordination between human subjects

has not yet been extensively studied. At a segmental level

[21,22,24], rhythmical oscillations of the legs or hands of two

seated subjects are coordinated according to the same patterns

as those already studied during rhythmical bimanual tasks in a single subject [15,16]. Since the seminal work of Hall

[11] about interpersonal distance, proxemic studies showed that people tried to maintain a personal space around them-

selves. Within this space, the presence of others is tolerated with difficulty and may lead to an embarrassing feeling [1].

Nevertheless, interpersonal distance is poorly documented when one subject has interactions during locomotion with another person rather than behaving in isolation or when one of them moves and the other remains stationary. When loco-

motor interactions occur without any verbal exchange, each

subject has to observe and make inference about the inten-
tions of the other subject and then to make predictions to

anticipate not only one’s future position but also the future

position of the other.

Since little is still known about the rules used by the CNS
to regulate locomotion in the presence of others, the aim of
the present study is to characterize the interaction between
pairs of subjects during locomotion. We make the hypoth-

esis that the timing and interpersonal distance may depend both

on the role played by each subject within the pair in terms of

leadership and on the amount of space they try to maintain

between themselves.

After obtaining their informed written consent about the

experimental protocol, we tested six male subjects (34

years) with no known perceptive or motor pathology. This

set of subjects was randomly divided into two subgroups so

as to constitute six pairs.

The experiment took place in a wide gymnasium in which a rectangular track was drawn on the ground (8 m × 2 m)
similar (but shorter) to the tracks used during fencing cham-

pionships (Fig. 1A).

The subjects were separated from each other by an initial

inter-subjects linear distance of 1, 2 or 3 m (D1, D2, D3). The

initial starting positions of each subject (I1, I2, I3) were drawn

on the track and were separated by 0.5, 1 or 1.5 m from the

middle (M). At the beginning of each trial, the two subjects

were accurately located face to face in an upright posture on

their starting positions.

After hearing a starting signal the subjects were instructed to walk backwards and forwards freely within the track

boundaries along the longitudinal axis (X) of the track dur-

ing the entire duration of the trial (20 s). However, one of

the subjects (called the leader L) tried to modify the initial

inter-subjects distance (D1, D2 or D3). L could achieve this
goal by producing variations in direction and velocity. Con-
versely, the goal of the second subject (called the follower

\[8\], completing polygons or walking along circular, elliptical

[9,23,25] or more complex curved paths [12]. Moreover, in

such experimental situations, all the features of the environ-
ment remain stationary throughout the entire displacement of

the subject.

Everyday, human subjects must plan and generate their

locomotor trajectories according to another person’s dis-

placements. For instance, this may be the case when two

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The experiment took place in a wide gymnasium in which a rectangular track was drawn on the ground (8 m × 2 m)
was to adjust his locomotor displacement and maintain the initial inter-subjects linear distance during the entire trial despite the direction and velocity changes of L.

For each pair, the experimental conditions (initial distances and roles of the subjects) were randomized. For each initial inter-subjects distance ($D_1$, $D_2$ and $D_3$), each subject took alternatively a specific role (L or F) during six trials of 20 s each. Therefore, each pair of subjects performed a total of 36 trials (6 trials $\times$ 2 roles $\times$ 3 distances).

The gymnasion was equipped with a set of 23 cameras (Vicon 8, Oxford Metrics Ltd.) allowing us to record at a sampling rate of 120 Hz and reconstruct the 3D positions of three light reflexive markers worn by the two different subjects moving simultaneously. The markers we used were located on the toes (2) and on the head (1). This latter marker was precisely aligned with the centre of rotation of the head in the horizontal plane and we assumed that it was representative of the subject’s global position in space.

In the present study, we focused on the antero-posterior component of the position of the subjects (X axis). We only retained trials in which any gaps in the data collection of the head and the feet positions were smaller than 10 consecutive missing samples (83 ms); then they were filled in using a polynomial algorithm. Data were next filtered with a Butterworth low pass, fourth order and recursive filter, with an 8 Hz cut-off frequency.

To characterize the locomotor behaviour of the subjects, we calculated, for each individual, their total travelled distance (TTX) that is the cumulated Euclidian distance along the X axis of the track. A cross-correlation procedure was applied to the linear displacements of both subjects (X_L and X_F) for each trial in order to calculate a correlation coefficient ($r$) after phase alignment, and a time lag between these two signals. We used the same calculation procedure on the displacements of the averaged position between the feet of each subject on the track. We assume that the time lag is similar to the response delay between the two subjects. We also measured the parameters of the steps for each subject (number of steps, step length, step duration and step velocity). In addition, we used the cross-correlation procedure on the time course of the distance between the feet obtained by each subject. Finally, we calculated separately the backwards and forwards velocities for each subject. In order to compare subjects pairs (6), roles within a pair (L or F) and initial and forwards velocities for each subject. In order to compare the different parameters of the subjects ($D_1$, $D_2$ and $D_3$), repeated measures analysis of variance (ANOVA) were performed on travelled distances, number of steps, step length, step duration, step velocity, backwards and forwards velocities, time lags and Fisher’s $z$-transform of correlation coefficients obtained from the cross-correlations.

An example of raw data is presented in Fig. 1B. Subjects walk backwards and forwards along a straight trajectory during the entire duration of the trials. A forward walk of L corresponds to a backward displacement of F. A peak on a curve corresponds to a direction change of the displacement (e.g. forward to backward). The subjects oscillate naturally within the boundaries of the track along X. The oscillations seem roughly to be in phase indicating that F tries to respect the instructions. The amplitude of the oscillations depends on the initial distance between the subjects, and, from a trial to another, the number of oscillations and the time between perturbations may vary according to the velocity of displacement decided by L. F can interpret the movements of L particularly for the smaller oscillations that can be overestimated, underestimated or even ignored. Fig. 1B shows that the motor responses of F are delayed according to the displacement of L. Nevertheless, F sometimes anticipates the displacement of L.

We have first analyzed the total distance travelled (TTX) by the subjects. TTX_L (15.57 ± 2.64 m) is greater than TTX_F (14.27 ± 2.49 m) than TTX_L (15.57 ± 2.64 m) but is significantly different between L and F for $D_1$, $D_2$ and $D_3$. For L, it appears that the initial distances can be divided in two distinct sub-categories. $D_1$ and $D_2$ do not significantly differ from each other ($p > 0.05$) whereas these two distances differ from $D_3$ ($p < 0.01$). For $D_1$ and $D_3$, L travels a greater distance than for $D_2$. For F each distance differs from the others ($p < 0.01$).

The value ($0.93 ± 0.08$) of the correlation coefficients between $X_L$ and $X_F$ obtained by a cross-correlation analysis (Fig. 2A) shows that the displacements of the subjects within the pair are highly correlated (Fig. 2B). The statistical analysis performed on the Fisher’s transform reveals that the initial distance has a critical influence on the quality of the correlation between the displacements of the two subjects ($F(2, 60) = 63.202; p < 0.001$) with decreasing values of $0.97 ± 0.03, 0.94 ± 0.06$ and $0.88 ± 0.11$, respectively, for $D_1$, $D_2$ and $D_3$. However, an interaction occurs between pairs and initial distances ($F(10, 60) = 2.956; p < 0.05$). Moreover, we observe different behaviours among pairs since three of them obtain similar correlation coefficients for the three initial distances ($p > 0.05$) and three other pairs obtain better correlations when subjects are initially separated by $D_2$ than by $D_3$ ($p < 0.05$). Another interaction occurs between pairs and leadership of the subjects: being leader or follower does not modify the correlation for all the pairs except one of them. In this particular pair the correlation coefficient differs when the roles of the subjects were alternated ($p < 0.05$).

Delays between $X_L$ and $X_F$ are equal to $-0.22 ± 0.13, -0.26 ± 0.11$ and $-0.29 ± 0.12$ s, respectively, for $D_1$, $D_2$ and $D_3$. Even if these values differ significantly ($F(2, 60) = 9.372; p < 0.001$), the post hoc comparison of means reveals the existence of similar and smaller lags for $D_1$ and
The step duration is also influenced by the role assigned to the subject. Indeed, not only we observe high correlations between the position of the heads and the feet position signals are very similar to those obtained on the averaged position of the feet of each subject. Moreover, the time lags between the foot position signals are very similar to those obtained between the head position signals with 0.211 ± 0.254 m/s, respectively. The step velocity is influenced by both the role of the subject (F1, 60) = 62.917, p < 0.005) with lower values for F than for L (1.92 ± 0.28 m/s) than for D1 and D2 (2.07 ± 0.35 and 2.11 ± 0.38 m/s, respectively). Although the step velocity is influenced by the initial distance, we observe, for each initial distance that the step velocity is always greater for L than for F (Table 1).

In addition, cross-correlations performed on the time courses of the distances between the feet of each subject indicated very low correlations between L and F (r = 0.2 ± 0.39) and no significant tendency. However, the same analysis performed on the averaged position of the feet of each subject on the track reveals similar results than the one already mentioned about the coordination of the position of the heads of the subject. Indeed, not only we observe high correlation coefficients (0.94 ± 0.06) but these coefficients diminish (F(2, 60) = 62.917, p < 0.005) with the augmentation of the initial distance (F(2, 120) = 13.663; p < 0.005) with lower values for D1 (1.92 ± 0.28 m/s) than for D2 and D3 (2.07 ± 0.35 and 2.11 ± 0.38 m/s, respectively).

Finally, the velocity of the head depends (F(1, 60) = 225.13; p < 0.005) on the role of the subject (L or F) whatever the direction of the displacement (forwards or backwards).

### Table 1

<table>
<thead>
<tr>
<th>Initial distances</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTXL (m)</td>
<td>15.74 ± 2.69</td>
<td>16.17 ± 2.53</td>
<td>14.79 ± 2.54</td>
</tr>
<tr>
<td>TTXF (m)</td>
<td>15.40 ± 2.08</td>
<td>14.71 ± 2.27</td>
<td>12.69 ± 1.97</td>
</tr>
<tr>
<td>Step</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number for L</td>
<td>36 ± 4.5</td>
<td>37 ± 4.8</td>
<td>36.5 ± 3.9</td>
</tr>
<tr>
<td>Number for F</td>
<td>37.8 ± 3.4</td>
<td>37.1 ± 3.3</td>
<td>35.4 ± 3.7</td>
</tr>
<tr>
<td>Duration for L (s)</td>
<td>0.536 ± 0.071</td>
<td>0.522 ± 0.068</td>
<td>0.523 ± 0.055</td>
</tr>
<tr>
<td>Duration for F (s)</td>
<td>0.502 ± 0.043</td>
<td>0.509 ± 0.044</td>
<td>0.529 ± 0.054</td>
</tr>
<tr>
<td>Length for L (m)</td>
<td>1.08 ± 0.17</td>
<td>1.11 ± 0.16</td>
<td>1.05 ± 0.13</td>
</tr>
<tr>
<td>Length for F (m)</td>
<td>1.04 ± 0.15</td>
<td>1.04 ± 0.16</td>
<td>0.95 ± 0.12</td>
</tr>
<tr>
<td>Velocity L (m/s)</td>
<td>2.05 ± 0.40</td>
<td>2.17 ± 0.43</td>
<td>2.03 ± 0.33</td>
</tr>
<tr>
<td>Velocity F (m/s)</td>
<td>2.09 ± 0.32</td>
<td>2.06 ± 0.38</td>
<td>1.81 ± 0.29</td>
</tr>
<tr>
<td>Head velocity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forwards for L (m/s)</td>
<td>0.756 ± 0.139</td>
<td>0.797 ± 0.145</td>
<td>0.759 ± 0.151</td>
</tr>
<tr>
<td>Forwards for F (m/s)</td>
<td>0.739 ± 0.110</td>
<td>0.721 ± 0.122</td>
<td>0.632 ± 0.109</td>
</tr>
<tr>
<td>Backwards for L (m/s)</td>
<td>0.821 ± 0.145</td>
<td>0.825 ± 0.129</td>
<td>0.743 ± 0.118</td>
</tr>
<tr>
<td>Backwards for F (m/s)</td>
<td>0.806 ± 0.130</td>
<td>0.755 ± 0.121</td>
<td>0.641 ± 0.107</td>
</tr>
</tbody>
</table>

**Notes:**
- TTXL and TTXF correspond, respectively, to the distance travelled by the leader and the follower.
- Mean and standard deviation of the step parameters: number of steps, step length (m), step duration (s), step velocity (m/s).
- Mean and standard deviation of the backwards and forwards velocities (m/s) performed by each subject.

**Results:**

- D3 (p < 0.05) associated with greater lags for D1 (p < 0.001).
- According to the calculation procedure, these results confirm on the one hand that the F’s displacement is delayed with respect to the L’s and, on the other hand, that this delayed response depends on the initial distance with smaller time lags for the shortest initial distances. However, the time lags also depend on the role assigned to the subject within the pair (F1, 60) = 58.808, p < 0.005) with lower values for F than for L (1.99 ± 0.35 and 2.08 ± 0.39 m/s, respectively) and by the initial distance (F2, 120) = 13.663; p < 0.005) with lower values for D1 (1.92 ± 0.28 m/s) than for D2 and D3 (2.07 ± 0.35 and 2.11 ± 0.38 m/s, respectively). Although the step velocity is influenced by the initial distance, we observe, for each initial distance that the step velocity is always greater for L than for F (Table 1).

**Correlations:**

- We also calculated the average number of steps, their mean amplitude and duration for each trial as well as the step velocity along the X-axis (Table 1). It appears that the number of steps depends (F1, 60) = 58.808, p < 0.005) on the role of the subjects (L or F) but the observed differences only occur for D1 (p < 0.005) and D2 (p < 0.05) but not for D3 (p > 0.05). The step length varies with the role assigned to the subjects (F1, 60) = 71.435; p < 0.005) with greater values for L than for F (1.01 ± 0.16 and 1.01 ± 0.15 m, respectively).
- Although the step length is influenced by the initial distance (F2, 120) = 17.305; p < 0.005) with smaller values for D1 (1 ± 0.1 m) than for D2 (1.08 ± 0.16 m) and D3 (1.07 ± 0.15 m), for each initial distance (Table 1), F always produced smaller steps than L (F(2, 120) = 7.237; p < 0.005). The step duration is also influenced by the role assigned to the subject but we observe a significant interaction with the initial distance the subjects have to maintain (F2, 120) = 12.46, p < 0.005). Indeed, whereas the step duration is greater (F(1, 60) = 12.826; P < 0.005) for L than for F (0.527 ± 0.065 and 0.514 ± 0.048 s, respectively), this phenomenon is mostly observed for D1 (p < 0.005) and D2 (p < 0.05) but it tends to disappear for D3 (p > 0.05). The step velocity is influenced both by the role of the subject (F1, 60) = 58.808, p < 0.005) with lower values for F than for L (1.99 ± 0.35 and 2.08 ± 0.39 m/s, respectively) and by the initial distance (F2, 120) = 13.663; p < 0.005) with lower values for D1 (1.92 ± 0.28 m/s) than for D2 and D3 (2.07 ± 0.35 and 2.11 ± 0.38 m/s, respectively).
or backwards) and the initial distance ($D_1$, $D_2$ or $D_3$). Indeed, L moves always faster than F ($0.78 \pm 0.13$ and $0.72 \pm 0.12$ m/s, respectively). In addition we observe an interaction between the role and the direction of the displacement ($F(1, 60) = 40.253, p < .005$). The higher velocities are obtained when L walks backwards ($0.80 \pm 0.14$ m/s) and F walks forwards ($0.73 \pm 0.13$ m/s) whereas subjects produce slower velocities when L walks forwards ($0.76 \pm 0.15$ m/s) and F walks backwards ($0.70 \pm 0.12$ m/s). The post hoc comparison reveals that all these velocities differ from each other ($p < .005$). Moreover, the velocity of the subjects is influenced by the initial distance ($F(2, 120) = 31.338, p < .005$) with lower values for $D_3$ ($0.69 \pm 0.11$ m/s) than $D_1$ and $D_2$ ($0.78 \pm 0.11$ and $0.77 \pm 0.11$ m/s, respectively).

The aim of the present study was to determine how two subjects interact when they walk face to face alternately forward and backwards and pursue opposite goals (changing or maintaining the interpersonal initial distance). Our results reinforce, at least for short interpersonal initial distances, the idea that in order to achieve social locomotor trajectories, the subjects use some coordination mechanisms depending both on the leadership and on the distance separating them. These coordination mechanisms can be analysed at a global level by considering the displacements of the entire bodies of the subjects as well as at a segmental level by considering the kinematics parameters of the steps.

At the global level, although F did not know in advance the displacements of L, he could basically use two different but complementary strategies to avoid loosing distance. On the one hand, an anticipative and risky strategy for F consists in predicting the instant of the direction changes of L and results in the fact that TTX$_F$ may be equal or greater than TTX$_L$ during a short time period. However, if the prediction of F is incorrect, TTX$_F$ increases much more than TTX$_L$. On the other hand, a reactive and secure strategy for F consists in waiting each direction change of L before initiating his own direction change. At the segmental level, our results concerning the step parameters mainly showing a lower number of steps associated with smaller step length, step duration and step velocity for F confirm that this reactive and secure strategy is mostly used by F.

Moreover, the average delays (200–300 ms) reinforce the idea that F reacted, rather than anticipated, to the displacements of L by perceiving visual information and extracting relevant features from the displacement of L. The differences between F and L obtained when calculating the backwards and forwards velocities also suggest that F adopted a strategy allowing him to quickly react to the displacements of L. For L, walking faster backwards than forwards allows to constrain F to rapidly trigger his direction change in order to avoid any collision with L. For F, walking slower than L, allows to create better biomechanical conditions to prepare the direction change to come than walking faster and to predict some forthcoming sensory events as well as the motor consequences of his actions. This is facilitated when L walks backwards because, quickly attracting F in his own direction, L can drastically reduce the inter subject distance by reducing his velocity and this can even lead the subjects to collide. For the shortest distances $D_1$ and $D_2$, the subjects probably tried to maintain a safety distance around them [11,17].

Nevertheless, leadership is not the only parameter that determines how the subjects interact and distance plays a major role in the regulation of locomotion for both F and L. Even though L and F travelled the same distance for $D_1$ they engaged in specific behaviours since L travelled the same distance for two of the three conditions ($D_1$ and $D_2$) whereas F systematically reduced TTX from $D_1$ to $D_2$. For $D_3$, this may be partly explained by the proximity of the track boundaries because subjects could only move back a few meters without getting out of the track.

Our results suggest that the CNS of each subject did not regulate locomotion on the basis of a slightly delayed copy (reproduction) of other’s actions. If it had been the case, one would have observed exactly reversed displacements across subjects during each trial with a perfect correlation and very short time lags for both the global displacements of the entire
body and the segmental parameters we measured. In the present study, the high correlation coefficients obtained with the cross-correlation analysis of the displacements of the head reveal that F coordinates his own displacement with respect to the perception of the global displacement of L. Moreover, the analysis of the coordination of the steps between the two subjects confirms this results since the steps performed by each subject are totally different in terms of number, length, duration and velocity. F tends to generate a behaviour that can be considered as being similar to the behaviour of L on a global point view but not on a purely segmental point of view neither at the spatial level nor at the temporal level.

Thus, we suggest that the subjects were totally involved in a bidirectional interaction with mutual influences of each of them on the other. They were producing high level imitation [4]: simply observing the other, they were able to interpret the view neither at the spatial level nor at the temporal level.

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