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Walking with avatars: Gait-related visual information for following a virtual leader

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A R T I C L E I N F O

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A B S T R A C T

Dynamic situations, such as interactive sports or walking on a busy street, impose high demands on a person's ability to interact with (others in) its environment (i.e., 'interact-ability'). The current study examined how distance regulation, a fundamental component of these interactions, is mediated by different sources of visual information. Participants were presented with a back and forwards moving virtual leader, which they had to follow by walking back and forwards themselves. We presented the leader in several appearances that differed in the presence of segmental (i.e., relative movements of body segments), cadence-related (i.e., sway and bounce), and global (i.e., optical expansion-compression) information. Results indicated that removing segmental motion information from the virtual leader significantly deteriorated both temporal synchronization and spatial accuracy of the follower to the leader, especially when the movement path of the leader was less regular/predictable. However, no difference was found between cadence-related and global motion information appearances. We argue that regulating distance with others effectively requires a versatile attunement to segmental and global motion information depending on the specific task demands. The results further support the notion that detection of especially segmental information allows for more timely 'anticipatory' tuning to another person's locomotor movements and intentions.

1. Introduction

Humans can coordinate their movements with each other efficiently in complex and dynamic situations. For example, humans can navigate successfully through crowds of people (e.g., Moussaïd, Helbing, & Theraulaz, 2011), drive a car through traffic (e.g., Lee & Jones, 1967), or play sports in a team-setting against opponents (e.g., Passos et al., 2011). A recurring component of such interpersonal coordination is distance regulation (Bourbousson, Seve, & McGarry, 2010; Ducourant, Vieilledent, Kerlirzin, & Berthoz, 2005; Okumura et al., 2012; Olivier, Marin, Crétual, Berthoz, & Pettré, 2013; Meerhoff, Pettré, Lynch, Crétual, & Olivier, 2018). Coordinating one's movements in a dynamic setting, where an agent has to continuously adapt to its environment, often imposes high demands on the agent's skill to interact with (other agents in) its environment (i.e., 'interact-ability', Meerhoff & de Poel, 2014). Through perceptuo-motor experience, humans learn to satisfy mutual goals by attuning to information presented by others and calibrating their actions accordingly (Fajen, Riley, & Turvey, 2009; Le Runigo, Benguigui, & Bardy, 2005; Sebanz & Shiffrar, 2009;

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Weissensteiner, Abernethy, & Farrow, 2011). Although recently the facilitative role of auditory information has been highlighted as well (Camponogara, Rodger, Craig, & Cesari, 2016), visual information is obviously most essential in such settings (Meerhoff, Bruneau, Olivier, & Pettré, 2018; Meerhoff & de Poel, 2014; Rio, Rhea, & Warren, 2014). The highly dynamic interpersonal co-ordination can be examined in a controlled setting using virtual reality (Olivier, Bruneau, Kulpa, & Pettré, 2018), which additionally allows for the manipulation of how visual information is presented (Lynch et al., 2018). Therefore, in the current study we adopt a locomotor tracking task in a virtual environment to examine how different sources of visual gait-related information affect the regulation of distance to another moving agent/object (see also Meerhoff, de Poel, & Button, 2014).

In this context, inspired by the dyadic interactions common to sports like fencing, Ducourant et al. (2005) used a follow the leader task to examine the effect of inter-person distance on locomotor coordination. In that study, whilst facing each other, the assigned follower was instructed to maintain constant distance to the assigned leader, who walked back and forth freely. Although the followers' step characteristics (e.g., length, velocity, frequency) were different from those of the leaders, the followers successfully maintained the initial inter-person distance. Based on this finding, Ducourant and colleagues argued that followers synchronize by behaving similarly in a general sense, rather than mimicking the leader's motion at the segmental level (e.g., step frequency and step size). This may imply that followers attune to global motion information (i.e., changes in optical size of the shape as a whole), rather than local information (i.e., relative motion of joint segments).

1.1. Global motion information

This global motion information Ducourant et al. (2005) alluded to, may be best described by the optical expansion-compression of objects of which the relative distance to the observer changes. It has been shown that the optical size of an object can be used to guide interceptive actions (Fajen & Warren, 2007; Savelsbergh, Whiting, & Bootsma, 1991; Zaal & Michaels, 2003), avoid collisions (Lynch et al., 2018; Regan & Gray, 2000) and regulate locomotion (Rio et al., 2014; Warren, Kay, Zosh, Duchon, & Sahuc, 2001). More specifically, the rate of change of the visual angle has been proposed as an optical variable used for regulating distance (Durgin & Li, 2011; Ito & Matsunaga, 1990; Regan & Gray, 2000). Indeed, Rio et al. (2014) found evidence for the idea that a follower may apply the strategy of nulling optical expansion (i.e., first derivative of the visual angle) to match the speed of a leader. However, when completely isolating global motion information by presenting a leader in the appearance of a sphere, Meerhoff et al. (2014) have shown that the temporal synchrony is decreased compared to a complete avatar appearance that displayed normal arm and leg motion. This provided first indications for the notion that although distance regulation can largely be guided by global information, it may be that some other motion information plays an important role in the timing of actions. In the current study, we extend on that finding by implementing a manipulation of movement-related information presented in the virtual leader.

1.2. Cadence-related motion information

Another pertinent source of locomotor-related visual information is the subtler lateral and vertical body sway that occurs during locomotion. This cadence information relates to the number of strides per unit of time and thus provides information about stride length and –rate (Dugan & Bhat, 2005). In fact, cadence has been shown to correlate significantly with several general gait parameters (e.g., gait speed, stride length, and stance phase duration, see Funato, Aoi, Oshima, & Tsuchiya, 2010; Kirtley, Whittle, & Jefferson, 1985). Humans' sensitivity to cadence-related information seems evident; even when one is not paying attention to another person's gait, people are known to consciously (Noy et al., 2017) but also subconsciously synchronize their cadence when walking side-by-side (Nessler & Gilliland, 2010; Nessler, Gutierrez, Werner, & Punsalan, 2015), which may even occur at the highest level of athletic sprinting performance (Varlet & Richardson, 2015; however see also Blikslager & de Poel, 2017).

1.3. Segmental motion information

Besides global and cadence-related motion information, local motion information (i.e., motion of body segments relative to other body segments) may also provide pertinent cues for regulating distance. After all, the global motion of the body as a whole is achieved through local movements of the legs, foot placement and posture. In the past, such segmental motion has been highlighted using point-light displays (Johansson, 1973). From these point-lights in motion, humans can perceive remarkable detail such as activity type (Giese & Lappe, 2002) and emotion (Dittrich, Troscianko, Lea, & Morgan, 1996). Moreover, it has previously been shown that point-light displays allow for anticipatory judgments about action intention (Diaz, Fajen, & Phillips, 2012) and upcoming movement outcomes (e.g., Cañal-Bruland, van Ginneken, van der Meer, & Williams, 2011; Huys et al., 2009). Moreover, Abernethy and Zawi (2007) revealed that the pickup of kinematics in some cases depends on the combination of multiple segments. By omitting certain segments from the point-light display, they examined what information was essential for predicting hitting direction in a badminton match play between experts and non-experts. Strikingly, no difference was found between experts when only an arm was included in the point-light display, but when the whole upper body was included, prediction of badminton striking direction was more accurate by experts compared to non-experts. This indicates that the relative motion of the body segments provides additional information about the movement outcome. Indeed, the motion of the body as a whole arises through a combination of segmental movements which may thus provide pertinent information to which one could attune its actions. In locomotion for example, a change in arm movements can indicate an upcoming gait direction change. Segmental motion information may provide pertinent information for inter-person locomotor interaction and thus distance regulation.

1.4. Body orientation and regularity

Following a leader has previously been shown to be constrained by perceptual and mechanical constraints as a result of the body orientation of a leader (facing away or towards the follower) and the regularity with which a leader moves (Meerhoff, de Poel, Jowett, & Button, 2017). This suggests that the perception of another walker depends on its movement similarity, which can be manipulated with the body orientation (Benton, Thirkettle, & Scott-Samuel, 2016). For example, the perception of speed changes depending on whether a runner is coming towards or going away from an observer (Meilinger, Garsoffky, & Schwan, 2017). Indeed, in a previous study we found that when a follower was facing the back of the leader (i.e., face-to-back, orientation F2B), distance was typically better regulated compared to when the follower was face-to-face (i.e., orientation F2F) with the leader (Meerhoff et al., 2017). A face-to-face leader may have been more difficult to follow because 1) its actions could not be directly mimicked (as the follower has to adopt backwards gait mode when the leader adopts forward gait mode) and 2) forwards gait is typically adopted at a faster pace than backwards gait (Ducourant et al., 2005), making it more difficult to follow a face-to-face leader because of this same forward–backward incongruence. Meerhoff et al. (2017) also showed that followers responded later and maintained distance more erratically with an irregular and therefore less predictable (cf., more competitive) leader. Moreover, an interaction effect revealed that if the predictability increased, the effect of orientation became more apparent.

1.5. Aims and hypotheses

It can be surmised that distance regulation is an important aspect of interpersonal coordination. The information may be portrayed by global-, cadence-related- or segmental-motion information. To address the question which information is attuned to when regulating distance, we adopted a cyclical forward–backward locomotor tracking task (similar to Meerhoff et al., 2014, 2017), where participants followed a life-size virtual leader. The advantage of using a virtual leader is that the leader's movements can be experimentally controlled and the leader appearance can be manipulated to portray a range of potentially relevant information sources. The appearance of the leader avatar was manipulated to emphasize specific types of potentially pertinent sources of visual information. The global motion information was isolated by portraying the leader as a sphere, cylinder and a mannequin that moved without limb movements. Similarly, the cadence-related information was highlighted by a mannequin that moved without limb motion, but *with* the cadence-related lateral and vertical sway. Finally, we represented segmental motion information using a point-light display. Our main hypothesis regarded the effect of these types of visual information. We hypothesized that removing segmental motion information would deteriorate distance regulation. Additionally, we manipulated the leader's *movement similarity* and *regularity* (see 'Leader recording') to explore how these important factors in distance regulation (Meerhoff et al., 2017) interacted with the leader appearance.

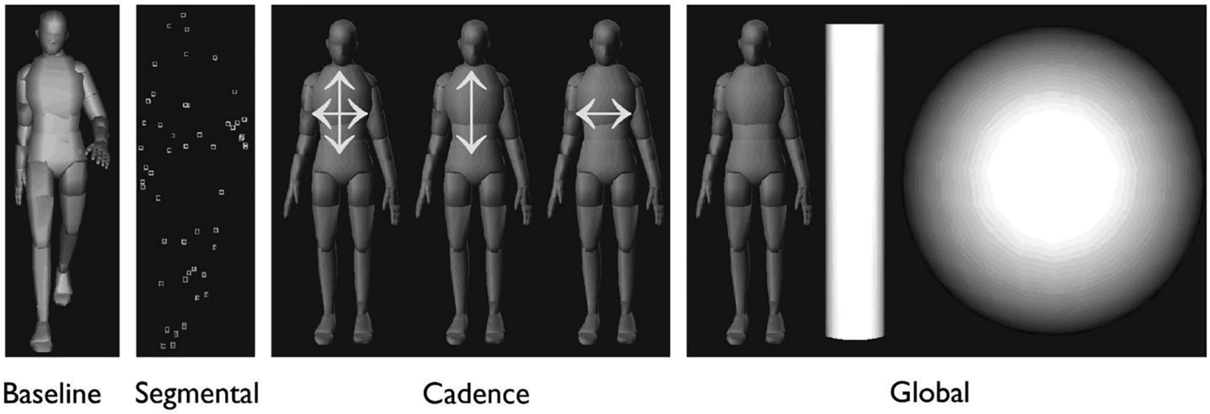

Fig. 1. Leader appearances as presented to the follower participants; the white arrows indicate the planes in which cadence movement was incorporated. From left to right: Baseline (Avatar), Segmental (Point-light), Cadence (Cadence XY, Cadence Y and Cadence X), and Global (Fixed, Cylinder and Sphere).

2. Methods

2.1. Participants

Eighteen reasonably active (self-reported exercise mean ± SD = 5.6 ± 3.2 h/week) male participants (age mean ± SD = 28.2 ± 5.4 years, height 1.83 ± 0.06 m) volunteered for the experiment. None of the participants reported any visual defects nor injuries that might influence their gait. A naïve confederate with similar characteristics (exercise 10 h/week, age 31 years, height 1.73 m) acted as the leader ‘participant’.

2.2. Leader recording

Prior to the follower participants’ data collection, the leader’s movements were recorded at 200 Hz using a 10-camera motion capture system (Vicon Motion Systems, Inc., Centennial, CO) to record the 50 *retro*-reflective markers on each joint and segment. A naïve model participant performed the role of the leader, who was instructed to walk back-and-forth, changing direction at a pre-set audio signal to assure an unbiased trajectory. The audio signal was presented at two levels of regularity (labeled ‘high regularity’ and ‘low regularity’), similar to Meerhoff et al. (2017). In the high regularity trials, the time between leader direction reversals was more regular (within-trial SD mean ± SD = 0.12 ± 0.15 s) compared to the low regularity trials (within-trial SD = 0.70 ± 0.12 s). The leader moved ‘to-and-fro’ whilst facing in the same direction, thus continuously changing between forwards to backwards gait mode. Based on 3D coordinates of the leader, its movements could be animated using Autodesk’s motion builder (Autodesk Inc., San Rafael, CA, 2013).

To examine the movement similarity highlighted by Meerhoff et al. (2017), the body orientation face-to-face (orientation F2F) and face-to-back (orientation F2B) were created by placing a virtual camera (at the same distance) in front or behind the leader, respectively. As such, when the leader participant adopted a forwards gait mode, it appeared to be moving *towards* the follower in orientation F2F, and *away* from the follower in orientation F2B (and vice versa for a backwards gait mode). By manipulating the

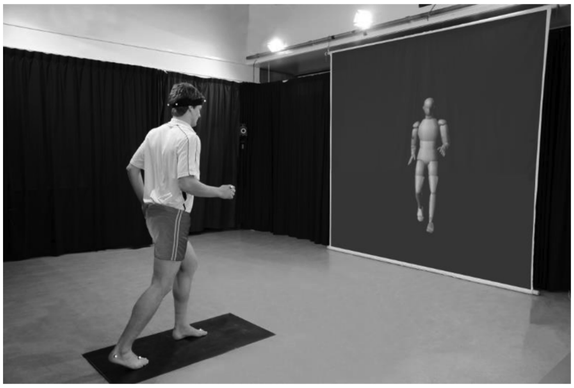

Fig. 2. Experimental set-up with the follower positioned in front the leader presented in the Avatar appearance with orientation F2F.

orientation, there was of course a visual effect (except for the symmetrical 'Cylinder' and 'Sphere' appearances, see 'Appearance') as the leader was facing towards or away from the follower. Moreover, given the difference between forwards and backwards gait (Ducourant et al., 2005), the orientation also yielded an effect on the movement similarity, with the orientation F2B being the most similar as the follower adopts the same gait mode as the leader (i.e., both in forwards gait mode, or both in backwards gait mode).

2.3. Appearance

In addition to recording the leader's movements at two regularity levels and animating the movements with two orientations (i.e., virtual camera positions), we animated the leader with eight different visual appearances (see Fig. 1). All appearances were based on the same movement trajectories of the leader; we only changed the 'skin' in the virtual environment. We included an 'Avatar' appearance with 15 moving segments as the baseline condition, with which we could compare the effect of each of the manipulated appearances. The Point-light appearance was included to highlight the segmental motion information. The cadence-related vertical 'bounce' and horizontal 'sway', directly derived from the c7 spinal marker, were included in the Cadence XY appearance. Additionally, the Cadence Y appearance only showed the bounce and the Cadence X appearance only showed the sway movements. The global motion information was isolated in three different appearances. In these conditions, the movements of the body segments were not animated. The back- and forward displacement of the leader was based on the movements of the c7 spinal marker along the movement axis (i.e., ignoring any side-to-side and up-and-down sway). One of these global appearances, the Fixed appearance, had the same shape as the baseline and cadence-related appearances, but moved without bounce and sway, and without moving segments. The second global appearance, the Cylinder, was included with the same height and width as the baseline appearance. Finally, the Sphere appearance was projected with a diameter equal to the height of the baseline appearance (an exact copy of Meerhoff et al., 2014). In the (online) supplementary material, a video of each appearance can be seen in orientation F2F (Videos 1 to 8 in the supplementary material).

2.4. Procedure

The participants were instructed to maintain the initial (virtual) distance with the life-size projection of the leader as it repeatedly shrunk and enlarged on screen (representing virtually approaching and receding, see Fig. 2). No instructions were given as to *how* (e.g., imitate steps) the participants had to follow the leader. To prompt the participant's attention to the task goal, the starting position was randomized either at 2.2 m, 3.2 m, or 4.2 m from the screen. The optical size of the leader was matched to the follower's starting position, that is, the perceived distance to the leader was the same, regardless of the participant starting position. The movements of the followers were captured with the same motion capture system as the leader, but the followers were tracked with only 13 *retro*-reflective markers. The synchrony between the display of the video with the leader and the motion capture of the follower was hardwired, using an analog signal encoded in the video to trigger the motion capture recording. Each trial lasted for 25 s, after which there was an eight second break. Each participant performed 8 (Appearance) × 2 (Regularity) × 2 (Orientation) × 3 (starting position) = 96 trials, yielding a total of 18 (participants) × 96 = 1728 trials. Due to unforeseen technical issues, 186 of these trials had to be excluded, leaving 1542 trials for further analysis. The excluded trials were equally distributed across appearance (ranging between 6 and 14% missing trials per appearance).

2.5. Data processing

The anterior-posterior movements of the participants' center of mass, based on the head markers, were subjected to a piecewise cubic spline interpolation to fill any gaps, after which the data was filtered using a second order low-pass Butterworth filter with a cut-off frequency of 5 Hz. All kinematic analyses were performed using MATLAB R2011a (The MathWorks Inc., Natick, MA, 2011). As the projection screen on which the leader was projected was fixed, the physical distance between the follower and the projection is meaningless with regards to 'regulating distance'. To operationalize distance with respect to the virtual displacements of the leader, we computed the Spatial Accuracy (*SA*), see also Meerhoff et al. (2017). With *SA*, we can assess the relative distance, as defined by a change in optical size, between the leader and follower in our experiment. *SA* is directly based on the rate of change ($\dot{\alpha}$) of the visual angle of the leader appearance at the eye of the follower. The optical variable $\dot{\alpha}$ directly reflects the change in relative distance to the leader; where an increasing distance has a negative $\dot{\alpha}$, a decreasing distance a positive $\dot{\alpha}$ and a perfectly maintained distance an $\dot{\alpha}$ of 0 $\text{deg}\cdot\text{s}^{-1}$. *SA* has the same magnitude as $\dot{\alpha}$, however, we set the sign of *SA* to reflect whether the follower was covering more (negative *SA*) or less (positive *SA*) distance than the leader: When the leader was moving towards the follower, *SA* was positive when the relative distance was decreasing (i.e., positive $\dot{\alpha}$), whereas when the leader was moving away from the follower, *SA* was positive when the relative distance was increasing (i.e., negative $\dot{\alpha}$). The evolution of *SA* over time is captured using the within-trial average (constant error, SA_{CE}), and within-trial standard deviation (variable error, SA_{VE}). SA_{CE} summarizes how close to the target (i.e., 0 $\text{deg}\cdot\text{s}^{-1}$) the participants were. SA_{VE} quantifies the consistency (or: stability) of the achieved SA_{CE}. For SA_{VE}, lower values indicate a less variable pattern, hence more stable coordination. In addition to the spatial accuracy, the temporal synchrony was assessed using the follower's response time (*RT*, in ms) to reverse direction after the leader had done so. For *RT*, the implied target is 0 ms.

2.6. Statistical analysis

Across 18 participants, we analyzed 1542 trials with two observations (each movement direction separately) per trial, yielding 3084 observations. Using R (R Core Team, 2013), a linear mixed effects models analysis (i.e., LMM, Zuur, Ieno, Walker, Salveliev, & Smith, 2009) was used to subject *RT*, SA_{CE} and SA_{VE} to an 8 appearance (Avatar, Point-light, Cadence XY, -Y, -X, Fixed, Cylinder and Sphere) × 2 orientation (F2F, F2B) × 2 direction (approaching, receding) × 2 regularity (high, low) Repeated Measures ANOVA (Goldstein, Healy, & Rasbash, 1994). For each outcome measure, we adopted the most parsimonious variance structure, based on the lowest AIC (Akaike's Information Criterion; Akaike, 1974). Subsequently, the final random effects model was selected stepwise by AIC. Note that this may result in degrees of freedom that vary slightly per dependent variable.[1] Results were summarized using least-square means (LSmeans; Searle, Speed, & Milliken, 1980) and the corresponding standard errors (SE) indicated as means ± SE. Post-hoc contrasts were tested for significance using Tukey HSD tests.

3. Results

3.1. Spatial accuracy

A significant main effect on SA_{CE} of appearance was revealed, $F(7, 3003) = 20.250$, $p < 0.001$ (see Fig. 3). The follower's spatial accuracy was significantly higher with segmental motion information appearances (i.e., Point-light and Avatar) compared to cadence and global appearances (p's < 0.05). The difference between the Point-light and Avatar appearances was not significant. Additionally, an appearance-orientation interaction ($F(7, 3003) = 2.463$, $p = 0.016$) was found. Post-hoc contrasts revealed that most appearances had a significantly higher SA_{CE} (i.e., worse performance) in orientation F2F (1.12 ± 0.07 $\text{deg}\cdot\text{s}^{-1}$) compared to orientation F2B (0.88 ± 0.07 $\text{deg}\cdot\text{s}^{-1}$). This effect was however not significant for the Point-light and Cylinder appearances.

[1] See https://github.com/Rens88/LinearMixedModels_walkthrough for details on how LMM can be used in a setting similar to this and on how to specifically calculate the degrees of freedom.

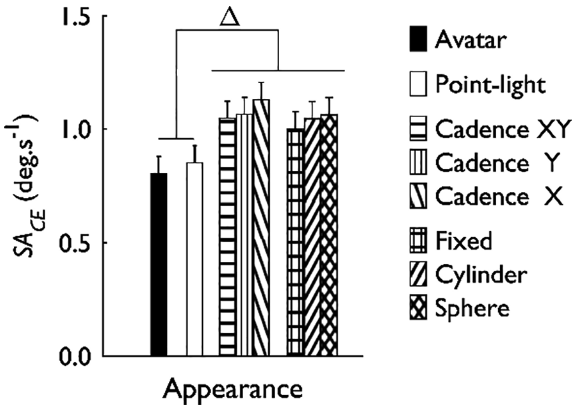

Fig. 3. Means (± SE) of spatial accuracy (SA_{CE}) for each appearance. The Avatar and Point-light appearances were significantly lower compared to all other appearances, as indicated with Δ.

A main effect for appearance ($F(7, 3024) = 16.626$, $p < 0.001$) revealed that SA_{VE} was significantly lower in the Avatar compared to all other appearances (see Δ in Fig. 4). Post hoc contrasts confirmed that with the Point-light leader, SA_{VE} was higher (i.e., worse performance) compared to the Cadence XY and Y appearances. Furthermore, a significant appearance-regularity interaction ($F(7, 3024) = 3.027$, $p = 0.004$) was found. For most appearances SA_{VE} increased (i.e., performance worsened) significantly in the low regularity compared to the high regularity trials; only the avatar appearance was unaffected by regularity.

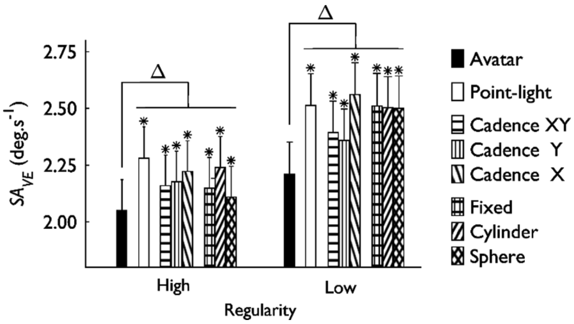

Fig. 4. Means (± SE) of SA_{VE} per appearance and regularity level. Appearances that were significantly affected by regularity are indicated with *. Furthermore, Δ highlights that the Avatar appearances overall had a significantly lower SA_{VE} compared to all other appearances.

3.2. Temporal synchrony

A significant main effect of appearance was found for RT, $F(7, 3017) = 44.017$, $p < 0.001$, which was accompanied by a significant appearance-regularity interaction, $F(7, 3017) = 8.166$, $p < 0.001$), as displayed in Fig. 5. Participants responded significantly faster with the Avatar appearance ($RT = 98.9 \pm 3.0$ ms) and Point-light appearance ($RT = 104.0 \pm 2.9$ ms) compared to all other appearances. The difference between Point-light and Avatar was not significant. RTs in all cadence and global appearances were similar, with mean RTs ranging from 112 to 118 ms. RTs were significantly larger (i.e., worse) in the low regularity compared to the high regularity trials for most cadence (XY and Y) and global (Cylinder and Sphere) appearances. The remaining appearances were not affected by regularity. Additionally, an appearance-orientation interaction was found, $F(7, 3017) = 8.848$, $p < 0.001$. Post-hoc contrasts revealed that only for the Fixed appearance there was a significant difference between orientation F2F ($RT = 115.9 \pm 3.1$ ms) and F2B ($RT = 108.4 \pm 3.0$ ms).

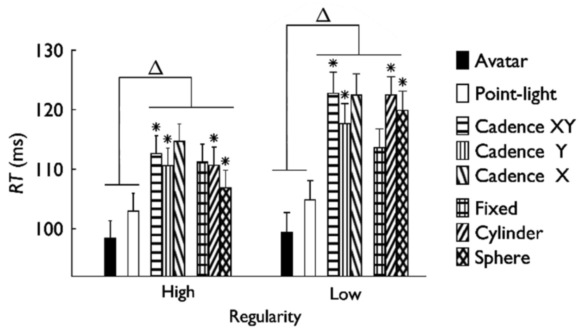

Fig. 5. Means (± SE) of *RT* per appearance and regularity level. Appearances that were significantly affected by regularity are indicated with *. Furthermore, Δ highlights that the Avatar and Point-light appearances overall had a significantly lower SA_{VE} compared to all other appearances.

4. Discussion

The current study addressed the role of different types of visual information on distance regulation in a follow the leader task. We differentiated between global, cadence-related and segmental motion information, each highlighted in different leader avatar appearances. Additionally, we manipulated key constraints in the stimulus (i.e., orientation and regularity) to further tease apart how these different information sources can be used by the follower. It was revealed that the follower performed most similar to the baseline Avatar appearance in the Point-light appearance, highlighting the importance of segmental motion information. In line with our expectations, reduction of segmental motion information in the visual display (i.e., all but the Point-light appearances) significantly reduced both temporal synchronization (*RT*) and spatial accuracy (SA_{CE}) compared to the baseline (Avatar) appearance; the spatial consistency (indicated by SA_{VE}) was significantly worse in all appearances compared to the baseline appearance. Additionally, it was shown that the effect of regularity was particularly strong for the cadence-related and global appearances, but not for the Point-light and Avatar appearance. This highlights that under less predictable circumstances (i.e., low regularity), the role of segmental motion information is even more important. The Appearance-Orientation interaction, on the other hand, did not reveal a consistent effect for the global and local motion information appearances.

Most notably, both the temporal synchrony (*RT*) and the spatial accuracy (SA_{CE}) deteriorated in the absence of segmental motion information. Moreover, without segmental motion information *RT* was affected by regularity, whereas for the Avatar and Point-light appearances the post-hoc contrasts did not reveal a significant difference. In our cyclical follow the leader task, each leader direction reversal required a timely – or even anticipatory – follower response, otherwise the relative distance would abruptly change and thus lead to a large error in task performance. An upcoming direction reversal in global motion information is merely indicated by a decrease in the rate of visual angle that occurs prior to a direction reversal, which may even be too small to reach discrimination threshold (Regan & Hamstra, 1993). In contrast, segmental motion information may have provided anticipatory information about the gait-cycle. That is, direction reversals imply altered inter-segmental patterns to decelerate the center of mass, for instance, by slightly tilting the trunk and altering the placement of the stance leg. In a judgement-oriented task, it has indeed been shown that the segmental motion of the preparatory movements of a tennis server can provide information about the upcoming action, in this example the serve direction (Cañal-Bruland et al., 2011). In other words, segmental motion information can be accessed to anticipate global movements.

On the other hand, Lynch and colleagues (2017) did not find a clear effect of the absence of segmental motion information in a highly controlled virtual reality experiment with real time interactions. In their study, participants had to navigate in a virtual world while an obstacle (i.e., walking avatar or cylinder), moving at a constant speed, crossed their paths. Arguably, this required less dynamic adjustments compared to our follow the leader task. As such, the additional benefit of segmental motion information might have been lower in Lynch et al.'s collision avoidance task. In future research, it might be possible to assess the effect of segmental motion information in more detail by addressing the synchrony at the level of inter-limb coordination (between participants). However, this was beyond the scope of the current work.

Interestingly, in the current study, followers did not benefit from any variant of the cadence-related information compared to the global appearances. Previously, it has been shown that cadence-related information can provide useful information (Funato et al., 2010; Kirtley et al., 1985). It may be that by isolating cadence information, the perceived potency of this information for distance regulation has been distorted. Cadence by itself does not inform about the direction of movement and, hence, (change in) distance to another walker. It can thus be surmised that cadence of gait in its current manipulation is not informative of relative distance. Together, our findings further strengthen the idea that segmental motion provides anticipatory information, which is in line with previous findings that followers had a temporal disadvantage in the absence of segmental motion information (Meerhoff et al., 2014). Interestingly, these findings highlight a different aspect of perception and action than put forward by Rio et al. (2014), who emphasize that following a leader is controlled by nulling the optical expansion. This difference can for the most part be attributed to the different task demands (following in one direction compared to back-and-forwards distance regulation), but it does highlight that besides the information sources directly available from the optic flow (e.g., rate of change of optical size), other sources such as one's body segments also provide relevant motion information in specific cases.

In sports, agents may move less predictably in order to gain a competitive advantage. For the perception–action process, it is thus crucial to be able to deal with these uncertainties (cf., deception, Sebanz & Shiffrar, 2009; Williams, Ford, Eccles, & Ward, 2011). The manipulation of regularity provided an analogy for competitive coordination, as the leader's movements were less predictable. As such, more pressure is put on the followers to attune to the information that best specifies upcoming actions. Only when segmental motion was not available, followers were affected by regularity, highlighting the importance of segmental motion to couple one's actions to someone else's (Diaz et al., 2012; Fine, Likens, Amazeen, & Amazeen, 2015). We thus infer that segmental motion information allows individuals to better anticipate whole-body movements of others, especially regarding less predictable movements. However, other studies have shown that despite segmental motion information being informative of future actions, it can also lead to the follower being more vulnerable to deceptive actions (e.g., Brault, Bideau, Kulpa, & Craig, 2012; Cañal-Bruland et al., 2011; Williams, Cañal-Bruland, & Hagemann, 2009). It is important to note that in our study regularity was only captured in terms of the interval lengths between direction changes. In a more representative setting, it must be considered that competitive behavior may also involve movements with the intention to deceive, as segmental motion information has the potential to be "dishonest" (e.g., Brault et al., 2012).

4.1. Flexible perception–action strategies

As in a typical interpersonal coordination setting, each of the types of motion information were simultaneously available in the Avatar appearance (Fine et al., 2015). This likely allowed participants to flexibly combine these information sources as required by the task. Note that, although segmental information may provide more detailed information about an agent's current state, it may not always be reliable and could even be deceptive (Brault et al., 2012). For instance, it is possible that a follower attuned more to the global motion information when the leader moved in a more regular/predictable way, whereas a follower could attune to segmental motion information when the leader moved less regularly. More specifically, it may be that followers flexibly combined sources within a movement trial. A direction reversal may be preceded by critical task-specific information available from the kinematics of the body segments (Meerhoff et al., 2017). Therefore, preceding the direction changes, followers may have relied strongly on the segmental motion information (explaining the tight temporal synchronization), whereas in between direction changes followers may rely more on global motion information (explaining the high spatial accuracy). Hence, followers appeared adept at attuning to different information sources as governed by the task requirements. This finding can for example be transferred to invasion sports, where agents continuously have to compete (with opponents) and cooperate (with teammates). This flexibility in perceptual strategy corroborates the notion that perceptual strategies are inherently variable as to accommodate the changing demands of the agent-environment system (Dicks, Button, Davids, Chow, & Van der Kamp, 2016). Furthermore, the visual system has been argued to show signs of degeneracy/redundancy (i.e., different input sources can support the exact same movement outcome; Edelman & Gally, 2001). For instance, humans can develop different gaze behaviors – and thus adopt different strategies of combining different types of motion information – to achieve the same outcome (e.g., Dicks et al., 2016; Seifert, Button, & Davids, 2013). Together, these findings suggest that the various types of information need to be dynamically combined: Skillful interacting (i.e., interact-ability, see Meerhoff & de Poel, 2014) may thus be characterized by flexibly attuning to various sources of information.

4.2. Leader orientation

The orientation of the leader influenced following behavior. In general, when the leader was oriented facing away from the follower (i.e., orientation F2B), the spatial accuracy was higher. As previously put forward by Meerhoff et al. (2017), this can largely be explained by the incongruence in gait mode: in orientation F2F the leader is walking forwards, whilst the follower has to walk backwards (and vice versa) to maintain the distance. The different characteristics of gait mode make it easier to regulate distance to someone who has the same gait mode. However, the interaction between Appearance and Orientation revealed that the effect of orientation was not significant for the Cylinder and the Point-light appearances. This may suggest that in addition to the mechanical constraints of gait mode, coordination is also influenced by a visual aspect of orientation. For example, it could be that a social component such as personal space influenced the coordination (see for example Gérin-Lajoie, Richards, & McFadyen, 2005). However, as the effect is absent in the Sphere appearance, the results are not consistent. The Point-light appearance may have been coordinated with differently because of the difficulty to observe orientation (de Lussanet & Lappe, 2012). This may also explain why the Point-light appearance showed reduced spatial consistency of the following behavior in general. Participants' perception of the leader may have been deteriorated due to the ambiguity of the body orientation of the leader in the Point-light appearance. Additionally, it is interesting to note that there was no interaction effect between the Appearance and the Direction. In a previous study, we showed that gait mode (i.e., walking with forwards or backwards gait) constrains the follower's ability to follow a leader (Meerhoff et al., 2017). The absence of a significant Appearance-Direction interaction might suggest that this constraint is based on the follower's gait mode and not affected by the visual appearance of the leader.

4.3. Virtual reality

By creatively using a virtual reality setting, some novel insights were generated in this study. Despite some obvious benefits – experimental control and possibility of visual manipulation – and the potential of using virtual reality to study interpersonal coordination (Olivier, Bruneau, Cirio, & Pettré, 2014), there were some important limitations that need to be considered for the implications of this work. The 2D display of the leader's movement in the current study may have affected the (relative) distance perception of our follower participants. Fortunately, similar to real life following (e.g., Ducourant et al., 2005) the leader was consistently followed with positive SA_{CE} values, indicating that the follower consistently covered less distance compared to the leader. Nevertheless, it would be interesting to examine the current findings in an immersive virtual reality, in which the third dimension of a virtual reality is simulated using, for example, a head-mounted display (e.g., Bailenson, Blascovich, Beall, & Loomis, 2003). Another aspect to be aware of in our virtual reality setting is that the coupling between the follower and leader was *uni*-directional. That is, the movements of the leader were pre-recorded and not responsive to the movements made by the follower. Indeed, interactions between people are typically asymmetrical rather than symmetrical, meaning they naturally imply a certain degree of leader–follower interaction, even when roles are not clearly allocated (De Poel, 2016; see also Meerhoff & de Poel, 2014). Using a more advanced virtual reality, it may even be possible to manipulate the coupling between leader and follower in a similar fashion as Kelso, de Guzman, Reveley and Tognoli (2009) did in studying the coordination dynamics of hand movements. Moreover, with the latest Virtual Reality technologies experiments can easily be scaled up from interactions between two to many (virtual) persons.

5. Conclusion

We have shown how segmental motion information provides an advantage in addition to global motion information in many aspects of distance regulation with other walkers. When the leader's movements became less regular/predictable, followers seemed to benefit from the information as presented through the relative motion of the segments. Nevertheless, it is unlikely that interpersonal coordination is achieved with segmental, cadence-related or global motion information sources alone. For inter-agent coordination, flexibly and effectively combining a variety of information sources may be crucial for goal-directed behavior. Skillful interacting – or interact-ability – may thus comprise of effectively attuning to pertinent sources of information, whilst avoiding becoming susceptible to deceptive movements. Future research should address the generalizability of these findings to other distance regulation tasks and, eventually, extrapolate the findings to more complex interactions with more than two persons such as crowds of people or sports teams.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.04.003.

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