



HAL
open science

Sustaining the Experience of Pair Natural Walking in Social Virtual Reality

Majd Bitar, Jean-Philippe Rivière, Rebecca Fribourg, Jean-Marie Normand,
Yannick Prié

► **To cite this version:**

Majd Bitar, Jean-Philippe Rivière, Rebecca Fribourg, Jean-Marie Normand, Yannick Prié. Sustaining the Experience of Pair Natural Walking in Social Virtual Reality. 3rd Workshop on Locomotion and Wayfinding in XR (LocXR) - IEEE VR 2025, Mar 2025, Saint-Malo, France. hal-04867351

HAL Id: hal-04867351

<https://hal.science/hal-04867351v1>

Submitted on 6 Jan 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

Sustaining the Experience of Pair Natural Walking in Social Virtual Reality

Majd Bitar*, Jean-Philippe Rivière,† Rebecca Fribourg,‡ Jean-Marie Normand,§ Yannick Prié¶

Nantes Universite, École Centrale Nantes, CNRS, LS2N, UMR 6004, 44300 Nantes, France



Figure 1: Walking in pair in social VR implies perceiving the other, either by direct sight (left), or, as proposed here, with audio or visual cues, such as a yellow aura on the ground (right).

ABSTRACT

Walking together is a basic social interaction, making it an essential feature to support in social virtual reality. Most research on locomotion in VR focuses on the motor aspect of walking, rather than on the cognitive or social aspects of social walking. In this paper, we explore walking in pairs, draw on observations from a pilot study, and propose some recommendations for enhancing the experience of pair walking in social VR. Using arm arm-swinging locomotion, we implemented two features based on movement rhythm, a footstep cue and an aura to enhance the awareness of one’s partner walking, that we tested in a custom virtual environment. The initial results highlight the potential benefits of our proposals, yet future work is needed to strengthen these findings.

Index Terms: Virtual Reality, Locomotion, Social VR, Navigation, Collaborative Walking, Social Presence

1 INTRODUCTION

Walking is a fundamental aspect of human social life, serving not only as a means of physical movement but also as a daily form of social interaction and communication. Be it to casually walk in a park with family while sharing news, for productive yet informal business meetings, or to discuss with educators or practitioners, the association of gentle physical exercise and discussion serves a lot of purposes besides getting from one point to the other. Walking together in social VR so appears to be an important activity that could be replicated in social VR.

Research on continuous locomotion in VR has primarily focused on the motor aspects of walking, exploring how to accurately and efficiently simulate the physical act of walking in virtual environments. Several systems have also focused on social aspects of teleportation in VR [14, 11], but teleportation is a locomotion means that is substantially different from continuous displacement. The cognitive and social dimensions of walking in VR, and the nuances

of how individuals perceive and react to each other’s presence during locomotion have received comparatively less attention.

We explored previous research related to collaborative walking in VR. Building on this foundation, we conducted a pilot experiment (n=8), observing pairs walking, and we derived recommendations from these observations. From there, we focused on the design of two specific cues intended to enhance the experience of walking together in VR using arm swinging locomotion: a visual aura to enhance separation distance awareness between walkers, and footstep sounds aligned with the frequency of arm movements. We built a custom virtual environment to evaluate these features and conducted a first evaluation (n=6) so as to assess their effectiveness in fostering a natural and socially engaging walking experience.

Our main contributions in this paper are a study of pair walking in the wild, a set of recommendations to facilitate pair walking in social VR, the design and implementation of two sensory feedback methods aiming at reducing separation distance between pairs in VR, and their preliminary evaluation.

2 RELATED WORK

Our focus is walking together in VR. In order to properly understand this problem we must first understand how individual walking in VR is achieved. Following that, we must look at what it means to be together in VR, and in turn how to model it. Finally, we must examine existing work in the context of walking together and identify studies that could inform us on how to enable users to walk naturally together in virtual environments.

2.1 Walking in VR

Various researchers addressed natural walking in VR. One approach breaks it down into two key aspects: the motor aspect (or travel), and the way-finding aspect [8]. When it comes to the motor aspect, different interesting locomotion categories enable navigation of open virtual environments within limited physical spaces [8]. The first category, known as *repositioning systems*, enables users to physically produce force to move forward while opposing contrary movements, causing the user to stay in place. This can be either passively (friction-free platforms) or actively (mechanical setups).

Redirection techniques are another solution for individual natural walking in VR. Systems implementing it allow users to move within a physical space while mapping their physical movements to adjusted virtual ones. For instance, when they approach a physical obstacle, such as a wall, they will need to turn in reality while

*e-mail: majd.bitar@univ-nantes.fr

†e-mail: riviere-jp@univ-nantes.fr

‡e-mail: rebecca.fribourg@ec-nantes.fr

§e-mail: jean-marie.normand@ec-nantes.fr

¶e-mail: yannick.prie@univ-nantes.fr

thinking they are walking straight by distorting what they see [2].

Finally, there are approaches based on proxy gestures. *Lower body gestures* locomotion involves using lower body movements to simulate walking. For example, users move their feet as if walking in place, and motion sensors track their movements to translate them into virtual movements. *Upper body gestures* locomotion relies on capturing movements of hands, head or torso and translating these movements into virtual ones. Current VR setups with inside-out tracking are able to track the movements of the upper body using cameras on the HMD and controllers, without the need for external sensors and equipment [3].

2.2 Walking together in VR

2.2.1 Walking together

Let us consider the locomotion methods discussed in the previous section with regards to walking together. Although *repositioning systems* allow natural walking, their main problem with regard to social walking is that they have mostly been designed with games or simulations in mind, and require extra hardware on top of current conventional VR setups, which most VR users do not have, hampering their use for casual activities. *Redirection techniques* do not seem adapted to group walking. Either these systems are only adapted to one person being cunningly redirected, or they require users to physically stop and turn around, which would cause group members to wait for each other to reset, disrupting immersion [12]. Finally, *proxy gestures* seem to be the best suited to implement walking in group, provided they do not necessitate expensive extra hardware to track users' movements. The *arm-swinging* locomotion method seems well suited for natural walking, as it greatly reduces cybersickness [9]. Additionally, it is intuitive and not overly fatiguing [9] as *lower body proxy gestures* methods would be.

2.2.2 Being together

Numerous studies already explored the concept of being together in virtual environments, social presence emerging as one of the key models used to address this phenomenon. Social presence refers to the sense of being together with others in a common space, it is a feeling of connection, awareness, and mutual understanding between individuals, even when they are not physically co-located [1]. Social presence in VR is sustained by using avatars to represent users in the VE, body and facial tracking to improve nonverbal communication and perception of the emotions of the other [4].

To our knowledge, no work addresses the question of how to integrate into VR the social attributes of walking together. However, a study on synchronization between pairs revealed that when individuals walk together, they tend to synchronize unconsciously and naturally [5]. In parallel, it has been shown that non-verbal synchronization can emerge in immersive environments [13] through different visual and vocal cues. Both studies open up the possibility of achieving such synchronization in VR through visual and audible cues induced by the locomotion technique. However, it remains unclear how to design cues for group synchronization.

2.2.3 Deciding together where to go

As discussed in Section 2.1, individual walking includes a way-finding aspect. Way-finding relates to the cognitive part of walking, where we choose a general destination and then make continuous cognitive decisions in order to reach it. However, in the context of walking in group, those cognitive aspects also include understanding each other's behaviors and reacting dynamically to them, on top of the mental load of active communication and coordination. Many works can be found in the literature on how to improve coordination [15] and provide group members with navigation information in order to take decisions [7]. However, there remains a lot of questions regarding the most natural and intuitive ways to do so, particularly when walking in VR.

2.3 Summary

We first reviewed locomotion techniques designed to enable walking in VR, and studied their potential with regards to group walking. Proxy gestures appeared as the best locomotion method, as they mimic some attributes of real walking without requiring additional hardware. We then highlighted that walking together in VR extends beyond locomotion, encompassing collaborative decision-making, social dynamics, and group synchronization through verbal and non-verbal cues. This exploration raised several questions, particularly about how to allow pairs to actively make decisions on where to go while preserving the feeling of being there together in the virtual environment.

3 PILOT STUDY

The technical and social aspects of walking together are intricate, making such behavior in VR far from straightforward, and the literature does not provide immediate solutions. To gain empirical insights and identify key features to support group walking in VR, we conducted a pilot study aimed at observing pairs walking together in real life during moments that required collaboration and communication while navigating a given path.

3.1 Procedure

Participants performed the experiment in pairs. Before beginning, they filled in a demographics questionnaire, including information on their height, gender, and whether they knew each other. They had to confirm they had no gait-related issues and consented for collecting data on body movements, as well as for video and audio recordings. Motion-tracking inertial sensors were then attached to each participant. The procedure was explained as a short stroll, where they had to go by nearby stores and then come back to the starting point. Along the path, we were interested in eight pre-defined points of interest (Fig. 2), where the pair was expected to make decisions or adjust their behavior. For instance, at Point 3, a crossroad required them to communicate and agree on which path to take, while at Point 5, a narrow passage accommodating only one person at a time prompted them to adjust their alignment and coordinate (either directly or indirectly) on who would go first. To prevent any group from rushing to complete the experiment, participants were informed they had 30 minutes to finish the task, which was more than sufficient to complete it at a natural walking pace. An experimenter followed the participants, capturing their movements with a camera and audio with wearable recording devices.

Once the participants were back at the starting point, they were told to remove the equipment as the experimenter prepared the video setup for a self-confrontation interview. Such interviews are used in social sciences and ergonomics to explore participants' thought processes and emotions during a given task [6]. The two participants were interviewed together, the interviewer showed them the video recording of their journey and questioned specific moments of interest. The discussed moments of interest were the same as the decision-making points shown in Fig. 2. The participants then explained their thought processes and how they evaluated the situation from their point of view.

3.2 Data collection

Five inertial sensors were used¹ per participant (one on each wrist, one on each ankle, and one on the forehead). They were synchronized before the experiment to ensure matching signal outputs. Audio and video recordings of the stroll were captured using a handheld camera and two wireless microphones². The self-confrontation interviews were audio recorded.

¹Movella Xsens dot sensors

²Rode Wireless Go

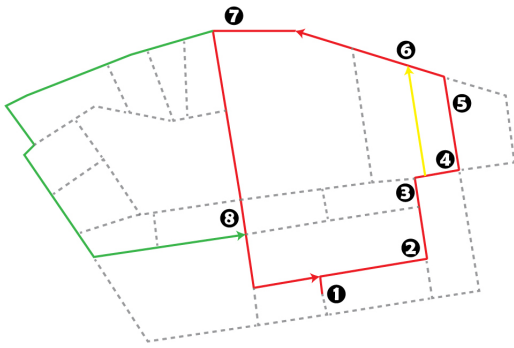


Figure 2. The path covered by the groups during the pilot study. The numbers highlighted are the *moments of interest* defined on the path. The dashed gray lines are paths that were not taken by any group. All groups followed the red path completely except for two groups that diverged from it at certain points. Group 4 skipped point of interest 5 and went through a different route to reach point 6. In addition, Group 2 diverged from the red path after the point of interest 6 and took a completely different route but then returned to point 8.

3.3 Participants

A total of 8 participants (5 Females, 3 Males) were grouped into 4 pairs, mean age 25.6, $\sigma=4.0$ (Min=21, Max=34). We chose participants that were familiar (colleagues and coworkers) mainly students and university employees, in order to make the social interactions more easy during the procedure. The average height of the participants was 170 cm, $\sigma = 11.2$ with the biggest height difference found in a pair of participants being 30 cm.

In the following, we refer to each group and participant using the format G#P#, where G# denotes the group and P# identifies the participant within that group. For example, (G1,P1) refers to Participant 1 of Group 1.

3.4 Analysis

The data collected was both qualitative and quantitative, collected from the sensors, video recordings, and interviews.

Motion signals were filtered to remove noise. The computed data provided information on the speed of each participant, their rhythmic pattern of footsteps and arm swings, and their head orientation. *Video recordings* of the walk were first presented to the pair during the self-confrontation interview, to help recall specific moments. They were also used to identify body gestures and map them to the motion signals captured by sensors. *Interview audio recordings* of the self-confrontation interviews were transcribed.

We created a groups x moments of interest matrix. We noted the recorded behavior of a given group at a given moment for each cell. This behavior was defined by what they encountered and reacted to in the environment, what they communicated verbally or non-verbally, addition to their thoughts and points of view as explained in the post-experiment interview, and finally the pattern of their movements in the time frame around the moment of interest. Following this matrix, patterns that were found across most groups were marked down and combined into a table.

3.5 Results

The first key observation in all groups was that *gestures were primarily used for navigation*. We classified these gestures into two categories: *conversational gestures* used to express one's ideas during a conversation through body language; and *navigational gestures* used to point out a location, a path, or to decide a direction to take. The frequency of use of navigational gestures varied between groups, when asked about the use of these gestures (G2,P1) replied: "It's true, I put them [gestures] in all directions", as she used them to point at different objects around the pair or to suggest taking a

given turn at a crossroad. Gestures were also used to translate participants' thoughts non-verbally. For example, (G3,P1) pointed in a direction and explained: "I'm wondering if we're going to go right or left".

Another observation was the presence of *active communication during decision-making moments*. While all participants engaged in verbal communication throughout the walk (e.g., chit-chat), it was particularly salient during decision-making and path navigation. For example, (G4,P2) explains: "That's why I asked (G4,P1), should we go left or right? And [my pair] told me right". It can be used to confirm others decisions, for example, (G1,P2) decided to go to the right without communicating this decision. (G1,P1) noticed that (G1,P2) was diverging and so chose to follow the pair to the right. To express the mutual agreement on going right (G1,P1) vocally informed (G1,P2) that they were going to the right.

Participants also demonstrated a *non-visual awareness of their partner's position relative to them*. This awareness was explained differently by participants. (G2,P1) felt closer to (G2,P2) and reacted based on that feeling. Later on in the interview, (G2,P1) realized that they were not close at that moment: "I felt (G2,P2) close, but (G2,P2) was not close to me... I had the feeling (G2,P2) was close.. I changed my mind to not bump into (G2,P2)". In another scenario, (G1,P1) was explaining his thought process at a crossroad: "We can choose to go right or left. So, there's my hesitation, and then, I don't know, I feel like it's (G1,P2) who is going right, and so I follow them". Finally, this awareness was present when indirect disagreements occurred, where (G4,P1) and (G4,P2) took different paths at a crossroad, and then, as they separated, noticed the absence of their partner and they both stopped and explained why (G4,P1): "(G4,P2) saw me looking left. And (G4,P1) knew that I was thinking about where we should go". Finally, (G4,P2) got closer to (G4,P1).

There was also a phenomenon of *dynamic adaptation in the speed and frequency of footsteps between pairs*. First, the relative pace between the pair seemed to affect their behavior, and they adapted to each other's pace. This was present at the beginning of the task, where (G1,P2) told (G1,P1) about the misalignment in pace, following that they both matched in speed and frequency, pointed out later during the interview (G1,P2): "I was going to say that this time I didn't feel like you were walking fast". This adaptation was a consequence of noticing a difference in the pace and footstep frequency relative to their partner; they saw or heard this misalignment and then reacted to it. Second, the sensors' data showed adaptation to pace and frequency. The movements of the lower body showed a high Pearson correlation (between ± 0.5 and ± 1) between partners across all groups. However, concerning the hand movements, a lot of variability was noticed. For some participants, we found a significant difference, which was expected considering that some participants preferred to walk with their hands in their pockets (G4,P1). Other participants were frequently using their hands for gestures and communication (G2,P1) and (G1,P1). Finally, a strong Pearson correlation was observed across all groups regarding head orientation, with participants consistently facing the same direction, which corresponds to the path they were following.

4 SUSTAINING PAIR WALKING IN VR

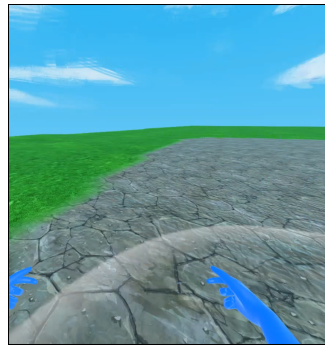
From these observations we drew some recommendations to help improving cognitive and social aspects of walking together in a virtual environment.

Recommendation 1 - Allow continuous verbal communication. We found that the pairs had continuous conversations, which they paused at decision making moments in order to discuss and take a decision. This highlights the importance of enabling pairs to exchange verbally at any time, as is already the case in most social VR systems.

Recommendation 2 - Enhance navigational gestures. We found



(a) The partner is moving in-front of the user and is visible in the user's field of view, causing no visual effect.



(b) The partner is out of the user's field of view, their *Aura* is visible, the white color informs the user that their partner is at close proximity.



(c) The partner is out of the user's field of view, the orange color of the *Aura* informs the user that their partner is further away.

Figure 3. The visual effect of the *Aura* and how its behavior changes based on the position of the partner with respect to the user.

that certain gestures were used for nonverbal communication, when pairs shared their points of view without interrupting the ongoing conversation. An interactive system could detect certain gestures and highlight/amplify them to notify other group members of these specific gestures.

Recommendation 3 - Facilitate separation distance awareness.

We saw that the separation distance of the pair greatly affected how they behaved. This encourages exploring ways to improve separation distance perception in VR, for instance by playing certain sounds, showing pop-up messages, or causing a change in the environment around the users.

Recommendation 4 - Promote non-verbal synchronization.

We found that nonverbal synchronization was always present between pairs. This hints towards transmitting the physical movements of users to their partner, thereby enabling synchronization between pairs. The transmission of the walking frequency detected from body tracking could for instance be achieved through visual or audio cues that would match this frequency.

5 A PROTOTYPE FOR WALKING IN PAIRS IN VR

We developed a prototype to evaluate how these recommendations could enhance the experience of walking together. We first created an arm-swinging implementation for locomotion, as we mainly drew our inspiration from upper-body proxy gestures. With regards to our recommendations, we focused on enhancing the perception of separation distance (Recommendation 3), and transmitting the sound of footsteps based on the frequency of physical movements (Recommendation 4). The following section details our implementation choices.

5.1 Arm Swinging

Arm-swinging locomotion is achieved by tracking the controllers' movement and computing movement vectors. The vectors are projected forward so that the front swings are more effective at moving the user than the side swings. For the direction of movement, and to enable moving forward while looking to the side, the system tracks the body and predicts the position and orientation of the user's hips, which define the direction of movement. Since other gestures, such as pointing at something, could collide with arm-swinging for locomotion, users must touch their controllers (detected by capacitive sensors) to enable arm-swinging. Finally, the frequency of the swing is calculated by computing the period (time) for one swing to be completed. The period is evaluated by the average value of the hand elevation over a certain period. Each arm has its period, and the transmitted overall frequency is the average between the two frequencies from both hands.

5.2 *Aura*: Separation Distance Awareness

To improve the perception of the separation distance between users, we implemented a continuous visual cue that reifies³ it. This *aura* provides users with information on how separated they are from each other. Its goal is to extend the perception of the partner in case participants could not see each other while walking together, by visualizing the separation distance as they move.

The *Aura* is represented as a circular pulse on the ground. It takes the metaphor of walking on water: when moving, the pulse starts from the feet and expands around the user, but when standing still it disappears. A user only sees the pulse from their partner and not their own. If the partner is moving while inside the user's field of view then their pulse is not visible (Fig. 3-a). The pulse is circular, transparent on the inside but colored at the border. The color of the border changes based on the separation distance. At close proximity (below a certain threshold), it is light gray (Fig. 3-b), but as the separation distance increases it starts shifting to become orange and then red at maximum proximity (Fig. 3-c). Above a certain maximum value, the pulse is not visible, and will not reappear until the pair rejoins.

5.3 Frequency Aligned Footsteps

Our system tracks the frequency of arm swings during locomotion and translates this into a sound that represents the rhythm of footsteps. This sound directly corresponds to the frequency of the physical movements, e.g., faster swings produce quicker footstep sounds. By enabling the perception of this rhythm, we aimed to help pairs synchronize their movements and maintain proximity to one another.

We only chose to enable users to hear the footsteps of other participants (not their own). While hearing one's footsteps has been shown to enhance presence [10], we made this design choice to prevent confusion. Indeed, we observed during pre-testing that hearing two distinct footstep sounds (one's own and others') while only perceiving the visual effect *Aura* for one audio cue led to inconsistency and potential disorientation. When footsteps are audible they are played in alignment with the frequency of swings of the user. 15 different footstep audio samples were used, each with a duration of 500 ms (sufficient to make audio pattern recognition difficult).

6 EXPERIMENTATION

We sought to evaluate the two features we designed to facilitate pair walking in VR. We hypothesized that transmitting the *frequency*

³Reification is the act of turning concepts into objects.

align footsteps would enhance rhythm perception, promoting synchronization and helping pairs stay closer. Additionally, we expected that the *Aura* would increase awareness of the separation distance, resulting in a reduced overall distance within pairs.

6.1 Environment

To test our assumptions, we designed a virtual environment composed of a virtual park of size 700*500 virtual meters. The park was designed relatively flat so that all areas were equally easily navigable. Moreover, we designed intersections to have approximately the same total number of possible path options regardless of the initial choice of path. This was done to avoid having one path leading to more options compared to other choices. We added different landmarks in the park (e.g., the big bench on Fig 1, right) to facilitate navigation and give an implied sense of destination motivated by curiosity to check out the landmarks. Footsteps and conversation audios were spatialized, decreasing in volume as the distance increased until complete cut off at approximately 18 virtual meters.

6.2 Setup

We used two Meta Quest Pro HMDs, connected over the same high-speed local internet network, located in separate rooms. If the primary locomotion method was arms swinging, users could also have occasional physical side steps. So as to avoid any inconvenience, we gave them more than 3x3m² of physical space to move. The environment was tested and optimized to achieve a minimum of 72 frames per second to ensure a smooth experience without performance drops. Recording the experience locally on the headsets while running the simulation was too expensive performance-wise, so we connected a third invisible device (PC) that followed the participants from a third-person point of view. In the simulation, only two avatars were visible, that of the participant and that of the experimenter. An invisible camera followed the pair from a third person point of view to record their general movement and path.

6.3 Protocol

The experiment had three conditions. Locomotion method and its parameters (speed and sensitivity) remained the same in all conditions, as was the use of voice communication. The differences between conditions were only related to *Aura* and audio footsteps.

No Footsteps and No *Aura*.

Footsteps alone: footsteps audio / no *Aura*.

***Aura* alone:** No footsteps audio / *Aura* effect.

The order of the conditions of the experiment changed per participant. We chose to consider only 3 conditions in our design, so as to test each feature for itself, excluding cross-effects, that could be tested in future work.

Participants started in a tutorial area, where they learned how to use arm-swinging for locomotion. Then they were teleported in the park, and were told that their task was to guide the experimenter, and that the choice of the path was up to them, based on what they found interesting to explore.

When ready, the first condition started, and after around 5 minutes, the participant filled out the per-condition questionnaire. Following that, the participant and the experimenter returned to the environment where they had stopped and continued their journey in the park for the new condition. The participant was not aware of the changing conditions, nor of the features being tested. This means that they were not knowledgeable on the *Aura* or how it behaved.

During the pretesting, we had seen that some pairs tended to stay close, while others separated easily, that is why the experimenter was included in the pair so as to eliminate too much variance in participants' behaviors. The experimenter had access in real time to the velocity and frequency for themselves and the participant, and to the separation distance. This allowed him to dynamically change his behavior based on the pattern of the participant. For example, if

a participant was always at close proximity, the experimenter would increase the separation to see the reaction of the participant. Similarly, if the participant was moving consistently at similar speed, then he would tend to decrease or increase his velocity to force the participant to react.

With regards to the conversation, a set of neutral and not emotionally questions and conversation topics had been decided before the experiment, so as to avoid any changes in behavior due to emotions.

The protocol was validated by the ethics committee of the University, IRB00013074, agreement n°11072024.

6.4 Participants

We conducted six sessions with six participants (4 Females, 2 Males), mean age 31.3, $\sigma=9.3$ (Min=21, Max=47). Four participants rated their prior VR experience less than 5 out of 10, while two (P1 and P3) rated their experience 6 and 5 out of 10 respectively. None of the participants used VR frequently. The participants had different educational backgrounds.

6.5 Data collection and analysis

We collected qualitative data using questionnaires and a post-experimental interview. After each condition, participants filled out a unique questionnaire containing three sub-questionnaires: the NASA-TLX Questionnaire to evaluate the participant's workload in different dimensions; the "Mutual Awareness" and "Behavioral Interdependence" sections of the Social Presence Questionnaire [1]⁴; an *ad hoc* questionnaire that included questions about the synchronization and awareness of the other to address aspects that we were interested in but that were not asked about in the other questionnaires. At the end of the session, participants filled out one final questionnaire regarding the features that had been implemented and tested in the experiment. We also had a final recorded post-experimental interview with participants, asking them questions regarding their understanding of the different features, notably whether they noticed the *Aura*, and understood what it meant. Other questions addressed their evaluation of the experience, and what was frustrating or caused them trouble. The participants shared their opinions and added insights to the data found in the questionnaires and numerical data.

Quantitative data was tracked and collected from the simulation: (i) the separation distance between the pair, (ii) the difference in speed, and (iii) the difference in frequency between the pair. The data was processed and visualized using Python.

6.6 Results

Considering the small sample of participants, we did not perform statistical analysis as ANOVAs at this stage but only descriptive analysis (only partially reported due to lack of space in this contribution). However, analyzing qualitative data allowed us to make several key observations about the proposed features.

For NASA-TLX questionnaire, all participants across all conditions reported low mental, physical and temporal effort (< 10), while providing high performance scores (> 15) for the system.

6.6.1 The *Aura*

Participants had split opinions about the *Aura*. Some of them understood its purpose and the underlying mechanism, which allowed them to use it effectively (P3, P4), leading to greater awareness of their separation. However, these participants also reported feeling distracted by the *Aura*, as P3 mentioned: "It was very useful, yeah. But also sometimes I think it was a bit... Maybe a little stressful. Because I was more conscious, that I was getting far from you

⁴The entire questionnaire was considered too lengthy, and only these sections were deemed relevant to our study.

and so I was more focused”. We can further validate this assertion with the quantitative data: P3 had low separation distance during *Aura* condition (7.1 ± 3.05) compared to the footsteps condition (12.5 ± 4.3), and P4 had the lowest during *Aura* (3.4 ± 0.6) followed by footsteps (4.8 ± 1.25).

Contrarily, some participants (P1, P2) were not able to clearly understand the *Aura* and chose to ignore it due to this confusion. In turn they did not make use of it, as explained by P2: “Yeah, but it didn’t really help understand how separated I was from [the experimenter]”. Remarkably, some participants (P5, P6) explained they did not directly understand the meaning behind the *Aura*, yet we measured a lower separation distance values during the *Aura* condition for these participants.

6.6.2 Frequency Aligned Footsteps

Similar to the *Aura* some participants found the footsteps useful and reliable (P1, P2, P5). These participants relied on the footsteps to stay closer to the experimenter, as they reported that they heard the audio cue of the steps and this helped them get closer and maintain proximity. This was confirmed by the quantitative data later on, as P5 explained: “When I was like left or right I didn’t see [experimenter] but I had the footsteps so I knew [experimenter] was here”. P5 also reported high social presence for the footsteps condition and had the lowest separation distance across different conditions.

When asked if she found the footsteps useful, P2 replied: “Yeah. In the last [condition], I noticed the sound. Yeah”. She also explained that it was easier and more natural to follow an audio cue than a visual cue when it comes to separation. Her quantitative data show that during the footsteps condition P2 maintained the lowest separation distance (5.75 ± 2.4), but got the highest distance for the *Aura* (13.07 ± 4.8). Meanwhile, we do not see similar results regarding the footsteps for participants (P3, P4, P6), as they did not rely on the footsteps. This was explained by P4: “It’s that maybe I heard them, but that’s clearly not conscious. I never pay attention to footsteps”. Similarly, P6 explained: “when you we walk with someone, we focus on the voice like in real life, we don’t hear the footsteps”.

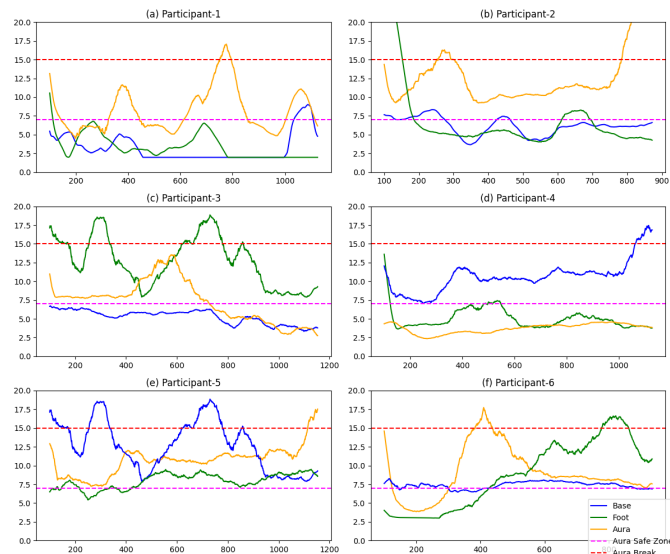


Figure 4. Separation distance over time for each participant. Each line corresponds to a condition of the experiment. Horizontal lines correspond to the low (magenta) and high (red) proximity thresholds for the *Aura*.

6.7 Discussion and future work

Data indicate that while both the *Aura* and footsteps have their strengths, their effectiveness is highly dependent on the individu-

als and the context in which they are used. Some of the participants found it more natural to rely on audio cues to maintain low separation, yet some other relied on the visual cues to stay closer.

We saw that the participants who understood the *Aura* are the participants that made the best use of this feature and made use of it to maintain low separation distance, but did not have a high impact on the social evaluation (P3,P4). However, participants who did not understand the meaning behind the *Aura* chose to ignore it and to not rely on it, thus the feature did not have any effect on maintaining the group behavior.

Regarding the *Frequency Aligned Footsteps*, it appears to be generally more effective in enhancing awareness and coordination, leading to reduced separation distance (P2,P3,P4). Nevertheless, the varying footstep frequency seemed to cause confusion to some participants (P3), which had consequences on the reliability of the footsteps.

In conclusion, this suggests that these features need to be carefully tailored to individual preferences and the specific demands of the environment. Further research could explore how to optimize these features to better accommodate diverse users needs and improve overall group dynamics.

6.7.1 Limitations

In our pilot experiment we chose participants that had some degree of familiarity within each others (co-workers, colleagues) in order to ease natural social interaction during the procedure. Further work should consider pairs with familiarity and no familiarity alike.

Our main experiment was constrained by the small sample size, leading to considerable variability in the data. Overcoming this variability requires a larger sample size and a more detailed analysis to produce more robust and generalizable findings. Further work should focus on expanding the sample size and refining the experimental design. Moreover, as already mentioned, the features can be further tested together to see the joint effect when combined.

7 CONCLUSION

Walking together is an important social daily activity, and allowing users to experience it in social VR seems important. Our review of related works showed that this topic has not been given the attention it deserves, with researchers having mainly worked on technology for walking in VR, or co-navigation within environments. To learn more, we conducted a pilot study where we observed pairs of participants walk together, which led us to establish 4 recommendations to facilitate pair walking in virtual reality: *Continuous verbal communication*, *Enhance navigational gestures*, *Facilitate separation distance awareness*, and *Promote non-verbal synchronization*. Following this pilot study, we developed an arm-swinging walking-in-place environment, and focused on two features aimed at facilitating the perception of the other: (i) the *Aura*, a visual feedback informing participants in a pair about the distance between them and (ii) *Footsteps aligned frequency*, providing a similar information through an auditory feedback. We then ran a preliminary experimentation which results show the potential of our feature proposals, yet more work is needed to assess them more thoroughly.

ACKNOWLEDGMENTS

We thank TRINOMA who provided us with the inertial sensors utilized in the pilot experiment.

This work was partly supported by a French government grant managed by the Agence Nationale de la Recherche as part of the France 2030 program, reference ANR-22-EXEN-0002 (PEPR eN-SEMBLE / CATS)

REFERENCES

- [1] F. Biocca, C. Harms, and J. Gregg. The Networked Minds Measure of Social Presence: Pilot Test of the Factor Structure and Concurrent Validity. In *4th Int Workshop on Presence*, Jan. 2001. 2, 5
- [2] D. A. Bowman, ed. *3D user interfaces: theory and practice*. Addison-Wesley, Boston, 2005. 2
- [3] A. Ferracani, D. Pezzatini, J. Bianchini, G. Biscini, and A. Del Bimbo. Locomotion by Natural Gestures for Immersive Virtual Environments. In *Proceedings of the 1st International Workshop on Multimedia Alternate Realities*, AltMM '16, pp. 21–24. ACM, New York, NY, USA, Oct. 2016. doi: 10.1145/2983298.2983307 2
- [4] G. Freeman and D. Maloney. Body, Avatar, and Me: The Presentation and Perception of Self in Social Virtual Reality. *Proc. ACM Hum.-Comput. Interact.*, 4(CSCW3):239:1–239:27, Jan. 2021. doi: 10.1145/3432938 2
- [5] L. Koban, A. Ramamoorthy, and I. Konvalinka. Why do we fall into sync with others? Interpersonal synchronization and the brain's optimization principle. *Social Neuroscience*, 14(1):1–9, Jan. 2019. doi: 10.1080/17470919.2017.1400463 2
- [6] V. Mollo and P. Falzon. Auto- and allo-confrontation as tools for reflective activities. *Applied Ergonomics*, 35(6):531–540, Nov. 2004. doi: 10.1016/j.apergo.2004.06.003 2
- [7] T. T. H. Nguyen, T. Duval, and C. Fleury. Guiding Techniques for Collaborative Exploration in Multi-scale Shared Virtual Environments. In *GRAPP International Conference on Computer Graphics Theory and Applications*, pp. 327–336. Barcelona, Spain, Feb. 2013. doi: 10.5220/0004290403270336 2
- [8] N. Nilsson, S. Serafin, F. Steinicke, and R. Nordahl. Natural Walking in Virtual Reality: A Review. *Computers in Entertainment*, 16:1–22, Apr. 2018. doi: 10.1145/3180658 1
- [9] N. C. Nilsson, S. Serafin, and R. Nordahl. The Perceived Naturalness of Virtual Locomotion Methods Devoid of Explicit Leg Movements. In *Proceedings of Motion on Games*, MIG '13, pp. 155–164. ACM, New York, NY, USA, Nov. 2013. doi: 10.1145/2522628.2522655 2
- [10] R. Nordahl. Self-induced Footsteps Sounds in Virtual Reality: Latency, Recognition, Quality and Presence. In *8th Annual Int. Workshop on Presence*, pp. 353–355. London, UK, Jan 2005. 4
- [11] J. Rasch, V. D. Rusakov, M. Schmitz, and F. Müller. Going, Going, Gone: Exploring Intention Communication for Multi-User Locomotion in Virtual Reality. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, CHI '23, pp. 1–13. Association for Computing Machinery, New York, NY, USA, Apr. 2023. doi: 10.1145/3544548.3581259 1
- [12] S. Razaque, D. Swapp, M. Slater, M. C. Whitton, and A. Steed. Redirected walking in place. In *Proceedings of the workshop on Virtual environments 2002*, EGVE '02, pp. 123–130. Eurographics Association, Goslar, DEU, May 2002. 2
- [13] Y. Sun, O. Shaikh, and A. S. Won. Nonverbal synchrony in virtual reality. *PLoS One*, 14(9):e0221803, 2019. doi: 10.1371/journal.pone.0221803 2
- [14] T. Weissker, P. Bimberg, and B. Froehlich. Getting There Together: Group Navigation in Distributed Virtual Environments. *IEEE Transactions on Visualization and Computer Graphics*, 26(5):1860–1870, May 2020. Conference Name: IEEE Transactions on Visualization and Computer Graphics. doi: 10.1109/TVCG.2020.2973474 1
- [15] T. Weissker, P. Bimberg, and B. Froehlich. An Overview of Group Navigation in Multi-User Virtual Reality. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces*, pp. 363–369, Mar. 2021. doi: 10.1109/VRW52623.2021.00073 2