Effects of Unaugmented Periphery and Vibrotactile Feedback on Proxemics with Virtual Humans in AR

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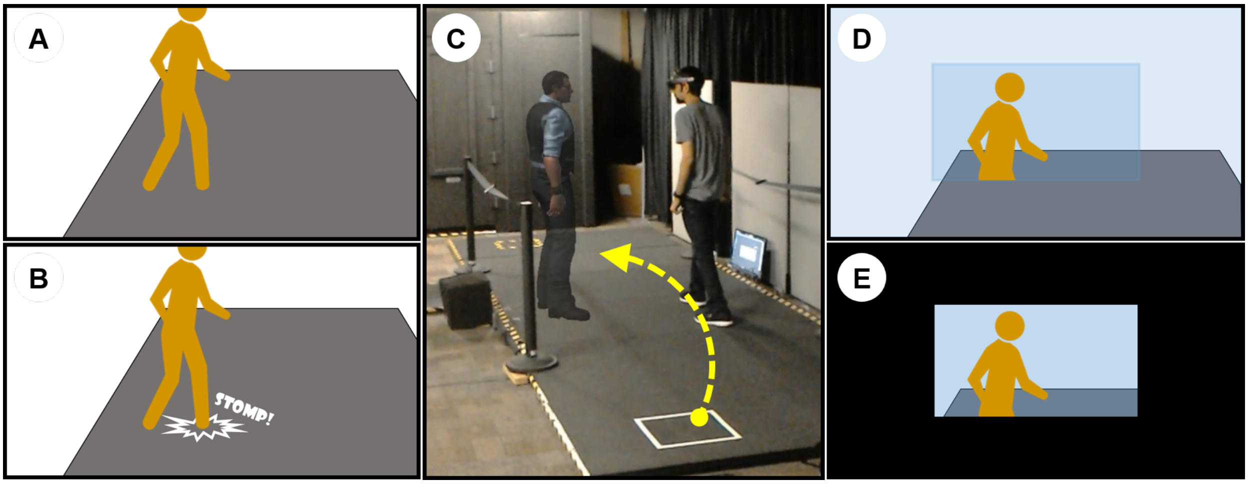

Fig. 1. Overview: Participants in our study performed a locomotion task while avoiding collisions with a real or virtual human obstacle (C). In this setting, we manipulated the virtual human's floor-based vibrotactile feedback (A: footsteps did not make any vibration, B: footsteps vibrated the platform); the user's visual field (D: both augmented central area and unaugmented periphery were visible, E: field of view was restricted to the augmented central area); and the behaviors of the human obstacle (standing, jumping, walking).

Abstract—In this paper, we investigate factors and issues related to human locomotion behavior and proxemics in the presence of a real or virtual human in augmented reality (AR). First, we discuss a unique issue with current-state optical see-through head-mounted displays, namely the mismatch between a small augmented visual field and a large unaugmented periphery, and its potential impact on locomotion behavior in close proximity of virtual content. We discuss a potential simple solution based on restricting the field of view to the central region, and we present the results of a controlled human-subject study. The study results show objective benefits for this approach in producing behaviors that more closely match those that occur when seeing a real human, but also some drawbacks in overall acceptance of the restricted field of view. Second, we discuss the limited multimodal feedback provided by virtual humans in AR, present a potential improvement based on vibrotactile feedback induced via the floor to compensate for the limited augmented visual field, and report results showing that benefits of such vibrations are less visible in objective locomotion behavior than in subjective estimates of co-presence. Third, we investigate and document significant differences in the effects that real and virtual humans have on locomotion behavior in AR with respect to clearance distances, walking speed, and head motions. We discuss potential explanations for these effects related to social expectations, and analyze effects of different types of behaviors including idle standing, jumping, and walking that such real or virtual humans may exhibit in the presence of an observer.

Index Terms—Augmented reality, virtual humans, locomotion, proxemics, vibrotactile feedback, field of view.

1 Introduction

Unlike immersive virtual reality (VR), augmented reality (AR) allows users to see both real and virtual objects. In particular, optical see-through AR head-mounted displays (HMDs) overlay virtual content on a users' natural view such that, with precise registration and tracking, the virtual content can appear seamlessly integrated into the real environment. When such AR technologies are applied to training simulations, trainees can practice their skills using a combination of real and virtual objects in the actual environments where the skills may eventually be used [20]. The behavior of the users in such circumstances are influenced by both real and virtual objects in that environment, therefore understanding how such real/virtual objects affect a users' behavior is of particular importance.

However, there are limitations with state-of-the-art optical see-through AR HMDs that may affect a users' perception of real and virtual content [31]. First, the virtual content is semi-transparent, which can cause visibility issues in bright environments, and distort color perception due to the additive blending. Second, the augmented visual region is limited to a small central area, which can lead to a real-virtual information conflict between the central and peripheral vision, and produce unnaturally cropped virtual content. Finally, currently available AR HMDs are limited to visual and audio augmentation. All of these characteristics can affect the perception of virtual content and the resulting actions and reactions [49].

Significant prior research has examined the characteristics of AR/VR displays—e.g., screen size, field of view, resolution—and their effects

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on the user's perception and behavior. That research supports the ideas that such characteristics can influence immersion [21, 48], task performance [28, 45], and behavior with virtual humans (VHs) [42].However, there has been relatively little exploration of the effects of the *unaugmented* real-world periphery in an optical see-through AR HMD, and, to our knowledge, no prior work has investigated its effects on real-virtual human interaction. We believe that the constant presence of an unaugmented scene in the periphery (the absence of virtual information), could have unexpected consequences, especially when the *augmented* central area is relatively small. In particular, the progressive disappearance of the body of a VH passing in and out of the small augmented region, and the total absence of the body in the periphery, may reduce sense of co-presence with the VH. However, we believe that these issues could be mitigated by other sensory information, e.g., vibrotactile feedback.

In this paper, we discuss and evaluate two related factors affecting locomotion behavior and proxemics with a virtual human in AR, and compare them with behaviors in close proximity to a real human. First, we examine the effects of the unaugmented periphery of the Microsoft HoloLens on human perception of a VH, and relevant changes in locomotion and proxemic behavior, by comparing two viewing conditions: an unrestricted but unaugmented periphery, and a physically restricted periphery. With an *unrestricted* periphery, the user is presented with a constant view of unaugmented peripheral imagery surrounding the augmented central region, and can thus perceive what we believe is an unnatural disappearance of part of a VH's body when the body crosses the boundary between the augmented central and unaugmented peripheral regions. With a *restricted* field of view, the user will *only* see the fully augmented central region, and because *all* imagery in the periphery will be blocked, we believe any "cropping" of VHs as they cross the boundary will appear more natural—it will be readily understood to be a consequence of the peripheral region being blocked. To test these ideas we examined how restricting the periphery affected a user's collision avoidance behavior for moving and non-moving VHs. Second, we examine the possibility that a vibrotactile stimulus associated with physical movement of the VH (presented in synchrony with the visual stimulus) could compensate for the negative effects of the unaugmented periphery. We compared two corresponding experimental conditions: visual presentation of the VH, or visual presentation of the VH *together with* simulated footsteps, felt as vibrations through the floor, similar to the approach taken by Lee et al. [33]. We examine whether the added vibrotactile feedback can indeed compensate for the restricted augmented visual field, and discuss the effects on perception and relevant locomotion behavior.

2 Related Work

2.1 Proxemics and Obstacle Avoidance

Proxemics and interpersonal distance are concepts related to how people perceive and act in the space between themselves and others. One may think of proxemics as involving a "bubble" of social space centered on and moving with a person, with multiple layers to the bubble, each with different social allowances [19]. People tend to keep a comfortable distance from others, which varies depending on the relationship to or behavior of the other person as well as the cultural background and situation [19]. Various studies have been performed in VR, where participants physically walked in a space while seeing one or more VHs. For instance, Bailenson et al. reported that participants maintained a larger space around a VH than they did for a similarly sized cylinder [4]. In a different study, they found that participants kept a larger distance from a VH when they walked towards the VH facing them with their front compared to their back [5].

A typical behavior involving proxemics is the avoidance of human or non-human obstacles. To avoid a collision, a walker must observe the surroundings and obstacles, predict the possibility of a collision, and adjust locomotion behavior accordingly [12]. Oliver et al. introduced minimum predicted distance (MPD) to quantify the risk of collision and showed that people adjusted their locomotion to reduce the risk [40]. Oliver et al. further showed that people exhibit similar collision anticipation/avoidance behavior with a VH even when using locomotion interfaces in VR [38]. In most cases, walking direction and speed are the parameters people change, but they can vary the types of adjustment based on the optimal strategy in each situation [14]. For a non-moving obstacle, people tend to favor adjusting their walking direction while keeping their walking speed unchanged [36]. However, in a smaller space, in crowded environments [37] with a higher uncertainty of the obstacle's behavior or surrounding environment [7], or in the presence of spatiotemporal constraints such as a revolving door [10], people tend to adjust the walking speed. Walking speed adjustments were also reported as an effect of a restricted field of view [24]. Regarding moving obstacles, the direction and angle of the obstacle's movement can influence one's strategy to avoid the collision. Basili et al. found that a human obstacle approaching perpendicular to the direction of locomotion caused participants to change their walking speed [7]. Huber et al. reported that the speed adjustment was favored only for acute angles while walking direction was always adjusted [22]. Finally, there has been some work comparing obstacle avoidance behavior in real and virtual environments. Fink et al. conducted a study comparing obstacle avoidance behavior with a real or virtual stationary obstacle during real walking in VR, and found a larger clearance distance and slower walking speed with the virtual obstacle compared to the real counterpart [15]. Argelaguet et al. further investigated obstacle avoidance behavior including human obstacles, and confirmed similar effects of a virtual human compared to a real counterpart [2]. They also reported a difference between a human and a non-human obstacle and that the orientation of the obstacle showed a significant influence on the locomotion behavior.

In reality, both humans in a dyadic pair actively coordinate their actions by the other person's actions [13, 39]; the actions performed toward a human would differ from those toward a cylinder [4]. In this paper we focus on obstacle avoidance behavior with a passive VH whose behaviors are independent of a participant's actions.

2.2 Field of View

Human peripheral vision is important for recognizing structure, shapes and maintaining body posture, self-motion speed, and heading among others [41]. Multiple studies have shown that when peripheral vision is restricted, one's situational awareness is limited [1], resulting in behavioral changes, such as turning the head more to compensate for the reduced field of view [3, 17]. In connection with the effects on situational awareness, Toet et al. conducted a study in which participants were asked to navigate in a complex environment [50]. Their results revealed that participants spent more time to traverse the environment when the field of view was restricted compared to an unrestricted visual field. However, a decrease in traversing speed was not observed for a horizontal field between 75 to 180 degrees [51]. Similar thresholds were reported in a visual speed perception study, in which participants underestimated the speed of motion with a central field of view of less than 60 degrees [43]. A large number of studies have reported the underestimation of distances on HMDs (see [35, 46] for a review of the literature). Jones et al. suspected the limited field of view in current-state HMDs might be a factor contributing to this effect and showed that an extension of the field of view resulted in improved distance judgments and changes in gait [25, 26]. Moreover, a restricted field of view was found to decrease target detection performance in VR [44] as well as in AR [45].

We are unaware of any related work considering the effects of field of view on obstacle avoidance behavior in VR or AR, although some suspected that the field of view might cause a difference [15].

2.3 Haptic/Tactile Feedback

Interpersonal haptic/tactile touch interaction between two people is known to elicit positive responses in people who are being touched [16, 18]. A large number of studies has shown similar positive effects of interpersonal touch in social interaction with a VH or a remote person. Basdogan et al. found that haptic sensations of the partner, such as when pulling or pushing through a co-manipulated virtual object by two remote persons, increased the sense of being together (i.e., *co-presence*) as well as task performance [6]. Similarly, Sallnäs reported that haptic feedback perceived through a shared virtual object increased presence, social presence, and the perceived performance when persons in two remote places passed a virtual object in a shared virtual environment [47]. In both of these studies, a visual representation of the respective other person was not provided. Regarding VHs, e.g., physically embodied or purely virtual, Kotranza et al. developed a mixed reality medical simulation in which trainees were interacting with a virtual patient that responded to touch and touched back [30]. They found that people treated the virtual patient more like a real human and rated the overall quality of communication as higher with touch feedback compared to without. Bickmore et al. reported that affect arousal and valence were associated with a squeezing behavior that a mannequin-based virtual agent exhibited [8]. Huisman et al. further attempted to simulate interpersonal touch with a simpler vibrotactile mechanism in an AR setup, and showed its effects on affective adjectives [23]. Recently, researchers also investigated the effects of indirect haptic/tactile feedback of a VH through a shared object—as opposed to the VH directly touching one's body. Lee et al. showed that social presence and affective adjectives could be improved by a subtle haptic force exchanged through a shared table with a VH in their mixed reality setup [34]. Moreover, they reported that perceiving vibrotactile feedback through a floor synced with a VH's footsteps can increase subjective ratings of social presence in VR [33].

We are unaware of any prior work exploring the effects of vibrotactile feedback through a shared object in the interpersonal space with VHs in AR. We believe that vibrotactile feedback that is visually synchronized with a VH's movements in AR should increase social and co-presence with the VH, as the external haptic sensation would be associated with the VH's presence [9], and as a result, relevant changes would be observed in the locomotion behavior.

3 Experiment

In this section we present the experiment which we conducted to investigate the effects of the previously discussed factors (real/virtual human obstacles, unaugmented visual field, floor-based vibrotactile feedback, and obstacle behavior) on locomotion behavior and proxemics in AR with a collision avoidance task.

3.1 Participants

We recruited 26 participants for our experiment, 14 male and 12 female (aged 20 to 50, $M = 25$, $SD = 6.13$). The participants were students or professionals from the local university community. All of the participants had correct or corrected vision; eight participants wore glasses during the experiment. None of the participants reported known visual or vestibular disorders, such as color or night blindness, dyschromatopsia, or a displacement of balance. Fifteen participants reported that they had used AR head-mounted displays before, and two of them rated themselves as a frequent user. All participants reported that they were right-handed and twenty-three reported that they were right-footed, which we confirmed with the Lateral Preference Inventory questionnaire [11]. We measured the interpupillary distance (IPD) of each participant before the experiment and applied it to render the virtual content on the HoloLens ($M = 6.18$ cm, $SD = .35$ cm). We also measured the eye height of each participant ($M = 1.57$ m, $SD = .25$ m).

3.2 Material

As illustrated in Figure 2, we built a runway-like platform with a size of 6.4 m (length) × 2.13 m (width). On each end, at a distance of 0.4 m, we marked a start position and an end position with white and yellow tape, respectively. They were symmetrically aligned around the center position where a human obstacle (described below) was located closer to the edge of the platform. Because the platform is about 5 cm raised from the floor, we added safety lines around the platform (see Fig. 1).

3.2.1 Human Obstacles

Each participant's task was to walk from one end of the platform to the other while avoiding an obstacle in between. At the center of their path we placed an obstacle, which was either a real human (RH) or a virtual human (VH). In a baseline condition, we asked participants to cross the platform without any obstacle. Both RH and VH exhibited three behaviors: (a) standing with idle behavior, (b) repeatedly jumping up and down, or (c) walking back and forth along the lateral axis of the platform, perpendicular to the participant's path (see Fig. 3). Each behavior was initiated with a bell sound that was used to inform participants to start walking (see Sec. 3.3.1). For the VH, we choose a male 3D character model with a similar height (1.75 m), age (early 30s) and body shape as the RH counterpart (a male actor). We could not match the race of the VH (Caucasian) and RH (Mongolian). The VH and RH wore sunglasses to avoid any effect of eye contact on locomotion behavior during the study. The initial position of the human obstacle was at the center of the platform as shown in Figure 2. For the VH's behavior, we used predefined animations, which were rendered using the Unity engine. For the RH, a trained real human actor mimicked the animations of the VH. In order to ensure a close match between the movements of the VH and RH, we provided the real human actor with two stage monitors that were located on the left and right side of the platform at the actor's position. On the monitors, we presented a real-time view of the platform and the movements that had to be matched. We verified that the real human actor's movements closely matched those of the VH by tracking the actor using an OptiTrack Duo optical motion tracking system before running the experiment.

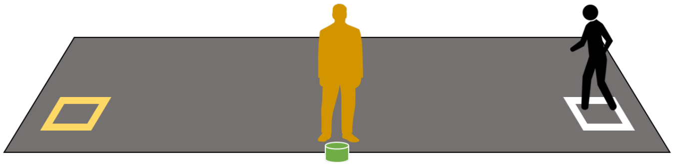

Fig. 2. Layout of the experimental platform: The white and yellow boxes represent the participants' starting position and the turning position, respectively. The green cylinder represents the position of the transducer attached to the platform. The real human or virtual human obstacle are positioned as indicated by the orange colored human model.

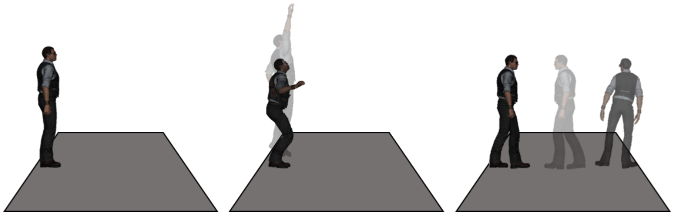

Fig. 3. Obstacle behavior from left to right: (standing) the human stands and looks around idly, (jumping) the human jumps in place around 22 times/min, and (walking) the human walks back and forth along the shorter edge of the platform at .27 m/s.

3.2.2 Head-Mounted Display

We used a Microsoft HoloLens for this experiment. As an optical see-through head-mounted display, the HoloLens provides a narrow (circa 30 degrees horizontally by 17 degrees vertically) augmented field of view in the central region of the total human visual field (circa 220 degrees horizontally by 120 degrees vertically) [41]. Therefore, a person wearing the HoloLens usually perceives a large unaugmented visual field in the periphery of the display. This means that if a virtual object is larger than the augmented central region, it will progressively disappear as it passes into the unaugmented region. Such vanishing visual information does not naturally occur in normal viewing for healthy observers, and may negatively affect the overall AR experience. This is a particularly challenging issue when a virtual human is presented in close proximity of the observer, since at no point can the entire body of the VH be seen through the HoloLens. This can give rise to a visual conflict between the real and virtual world (see Fig. 4 left column). In order to avoid such a conflict we devised a thin physical cover for the HoloLens that attaches to the inner side of the visor, which blocks the unaugmented peripheral visual field (see Fig. 4 right column). The two

Fig. 4. View conditions and captured photos for each condition: (left) unrestricted, (right) restricted. The augmented field of view is 30°x17°. The images here show only a small peripheral area because of photographing constraints. The peripheral FOV perceived through the HoloLens is much larger.

considered viewing setups in this experiment were therefore as follows:

- Unrestricted View: Participants could see both augmented central and unaugmented peripheral regions, allowing real-virtual visual disappearance/reappearance (Fig. 4 left column).
- Restricted View: Participants could only see the augmented central region, eliminating the disappearance issues, but reducing the overall field of view (Fig. 4 right column).

3.2.3 Footstep Vibration

To induce visually synchronized vibrations for the jumping and walking behaviors on the platform, we attached a transducer to the edge of the platform near the VH's position. We used the ButtKicker LFE Kit[1] covered with a black sound-proof box. To generate the vibrations, we used a client-server model. The client running on the HoloLens rendered the VH on the platform and sent a message to the server for all collisions between the VH's foot and the platform. The server played a prerecorded low-frequency sound—a footstep sound on a wooden floor with a low-pass filter applied— for the impacts, which was fed to the transducer through the ButtKicker amplifier. The communication between client and server was done through the Unity HLAPI, and both were connected to an ASUS RT-AC5300 high-speed router. Since the VH's animations were pre-recorded, collisions between the character's feet and the floor did not have to be computed in real time. The effects were synchronous visual cues on the HoloLens and vibrotactile cues on the platform.

3.2.4 Tracking

During the experiment, we tracked the participant's head position and orientation as well as the position of the real human actor. In particular, we logged the HoloLens' pose estimation in the tracking space. In order to ensure accurate pose estimations by the HoloLens, we made sure that sufficient feature points and light were available in the entire walking area. For the RH, we used an OptiTrack Duo mounted on the ceiling and had the RH actor wear an infrared (IR) marker on his head. All tracking data was logged at 50 Hz on the server.

3.3 Methods

We chose to use a within-subjects design in this experiment due to the expected interpersonal differences in locomotion behavior in such experiments [15]. The independent variables were

- *Obstacle type* (Real Human, Virtual Human),

[1]http://www.thebuttkicker.com

Table 1. Overview of the study conditions. Each column refers to factors we controlled. The rows indicate the tested combinations. The three obstacle behaviors refer to Standing, Jumping, and Walking. * indicates blocking factors, and the structure of the table represents our blocking scheme.

Obstacle*	View*	Vibration*	Behavior
Real Human	Unrestricted	-	S,J,W
	Restricted	-	S,J,W
Virtual Human	Unrestricted	ON	S,J,W
		OFF	S,J,W
	Restricted	ON	S,J,W
		OFF	S,J,W

- *Obstacle behavior* (Standing, Jumping, Walking),
- *View condition* (Restricted, Unrestricted), and
- *Vibrotactile feedback* (ON, OFF).

Due to the time overhead for changing the obstacle type and the cover between view conditions in the experiment, we chose to use a randomized block design with the obstacle type and view condition as blocking factors, i.e., we tested these conditions as a block, but we randomized the order of the blocks as well as the conditions that were tested within the block. For the RH conditions, the vibrations were naturally accompanied by the RH's footsteps, so we did not add additional vibrotactile feedback via the transducer. For the VH conditions, we further used vibrotactile feedback as a blocking factor, and also randomized the order of its levels. We used pink noise with earphones in all conditions to eliminate the difference—between VH and RH, and between each footstep sound of RH's—in auditory stimuli. For each combination, we performed two repetitions, resulting in 36 trials per participant. Additionally, at the beginning of the experiment, participants performed two trials without any obstacle for each view condition in order to gather baseline locomotion data. Table 1 summarizes the conditions.

3.3.1 Procedure

Prior to the experiment trials, participants gave their informed consent and filled out a demographic questionnaire, the Lateral Preference Inventory (LPI) [11], and the Simulator Sickness Questionnaire (SSQ) [27]. After the participants completed the pre-questionnaires, they received written task instructions and the experimenter made sure that they understood the tasks in a walk-through of the experiment.

At the beginning of each trial, participants were instructed to stand still at the start position (inside the white box, see Fig. 2). Once they heard a bell sound via worn earphones, they walked naturally at a comfortable pace to the turn position at the other end of the platform (yellow box). When they arrived at the turn position, they were asked to stop for three seconds, turn on the spot, and head back to the start position, again walking naturally at a comfortable speed. After arriving at this position, we again asked them to stop for three seconds before turning around. These three-second stops ensured that the start-stop walking segments were clearly distinguishable in the tracking data, and prevented participants from adopting a curved trajectory at each end. Note that changing walking speed and direction may not be necessary for the walking obstacle depending on a participant's natural walking speed; the participant had to decide while walking.

We regarded walking from the start position to the turn position and coming back to the start position as one trial, consisting of two movement segments. Participants performed 40 trials in total consisting of trials with no obstacle (4 trials), RH obstacle (12 trials), and VH obstacle (24 trials). The experimenter helped them adjust the HoloLens correctly each time the view condition changed. For the VH conditions, we divided trials into four groups based on the view condition (2 levels) and vibrotactile feedback (2 levels). Upon completion of each group, participants took off the HoloLens and filled out post-group questionnaires that started with an introduction of the VH as "Jack." After completing all trials, participants filled out post-experiment question-

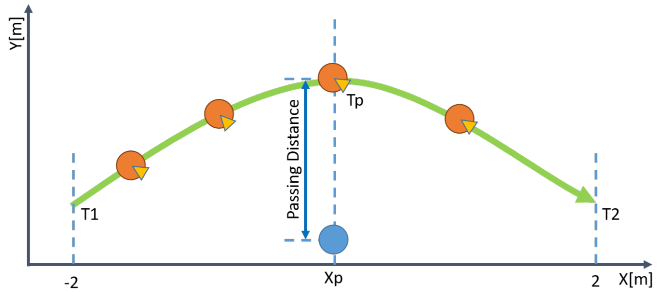

Fig. 5. Illustration of the behavioral data analysis: The blue circle indicates the obstacle, and the orange circles the participant at different timestamps. The green line indicates the participant's walking trajectory (here from left to right). The yellow triangles indicate the participant's view direction. When participants passed the obstacle (at timestamp T_p), the x-axis positions of the obstacle and participant matched (at X_p). The *passing distance* is computed as the distance between the participant and the obstacle at time T_p. The *trajectory length* (L) is the length of the green line. The *walking speed* is computed as $L/(T_2 - T_1)$, with the timestamps T_2 and T_1 when entering and exiting the region of interest $[-2\,\text{m}, 2\,\text{m}]$ on the x-axis.

naires consisting of the SSQ and open questions, and received monetary compensation.

3.3.2 Behavioral Measures

While performing the locomotion task, participants' head position and orientation were continuously tracked by the HoloLens tracking system. As illustrated in Figure 5, the platform's longer edge is aligned with the x-axis and the shorter edge is aligned with the y-axis in a right-handed Cartesian coordinate system with the obstacle's initial position as the origin $(0,0)$. The logged tracking data ranged from the start to the turn position on the x-axis, resulting in an overall range of $[-3\,\text{m}, 3\,\text{m}]$. The considered range along the y-axis was $[0\,\text{m}, 2.13\text{m}]$. However, in order to account for observed variability in acceleration/deceleration at the starting/turning positions, we limited our analysis of the considered range along the x-axis to the central range of $[-2\,\text{m}, 2\text{m}]$. As discussed in Section 3.3.1, each trial consisted of two movement segments (walking back and forth), which we analyzed separately. From the tracking data we extracted the following variables (see Fig. 5). Note that we used the forward vector as an estimate of the gaze direction.

- *Passing distance*: The distance on the y-axis between the participant and the obstacle at the moment when the participant passed the obstacle, i.e., the moment when the x-axis position of the participant and the obstacle matched.
- *Walking speed*: The average walking speed for each path.
- *Trajectory length*: The path length of the trajectory that participants walked.
- *Head motion*: We calculated the head motion of the participant by calculating the length of the trajectory the participant's gaze (forward vector) traveled on a unit sphere that surrounds the head (i.e., origin of the forward vector).
- *Observation ratio*: The ratio of time devoted to looking at the obstacle (we computed this with an angle of ± 10 degrees from the gaze direction) before they passed the obstacle.

3.3.3 Subjective Measures

Results from previous studies considering VHs imply that one's perception of a VH regulates one's behavior to the VH (cf. Sec. 2). Hence, we included subjective measures assessing how the participants felt about the VH. We measured social presence (the likeness to an actual human being), co-presence (the sense of being together), perceived physicality (being able to physically affect one), and perceived intelligence. Therefore, we used the Social Presence Questionnaire (SPQ) by Bailenson et al. [5] and the Co-Presence Questionnaire (CPQ) by Basdogan et al. [6]. In both SPQ and CPQ, we modified each question to refer to the VH as "Jack" instead of "the person" or "the other person." For CPQ we also removed inappropriate questions related to the manipulation task that was used in their study. Each question was rated on a 7-point Likert scale. Additionally, we designed four task-related questions to measure how much participants perceived the VH as being intelligent and as being able to physically affect them; each of these questions was rated on a 5-point Likert scale. All questions are listed in Table 2.

3.4 Hypotheses

Based on the related work, our study design, and data from a pilot evaluation, we formulated the following hypotheses for the behavioral measures:

H1 Participants will exhibit different (e.g., less natural, energy efficient, or slower) locomotion behavior with the VH obstacle compared to the RH obstacle.

H2 Participants will exhibit different (e.g., less stable, efficient) locomotion behavior with more head motion when the field of view is restricted compared to when it is unrestricted.

H3 Participants will exhibit locomotion behavior with the VH obstacle that is more similar to the RH conditions when the field of view is restricted (i.e., the real-virtual conflicts in the periphery of the display are removed) than when it is unrestricted.

H4 Participants will exhibit locomotion behavior with the VH obstacle that is more similar to the RH conditions when footstep vibrations are induced than when they are absent.

Moreover, we formulated the following hypotheses for the subjective measures:

H5 Participants will feel higher social presence and co-presence with the VH in the restricted view condition (i.e., without real-virtual conflicts) compared to the unrestricted condition.

H6 Participants will feel higher social presence and co-presence with the VH and feel higher perceived physicality of the VH when they experience vibrations seemingly caused by the VH's behavior.

4 Results

We first present the descriptive and inferential statistical analysis of the quantitative behavioral measures, followed by the subjective questionnaire responses.

Table 2. Questionnaire used to assess the participants' perception of the VH obstacle (called *Jack*) with the dimensions social presence (SP1 to SP5), co-presence (CP1 to CP5), perceived physicality (PH1 to PH3), and perceived intelligence (PI). The social presence and co-presence questions were answered on 7-point Likert scales, and the perceived physicality and intelligence questions on 5-point Likert scales.

ID	Question
SP1	I perceive that I am in the presence of Jack in the room with me.
SP2	I feel that Jack is watching me and is aware of my presence.
SP3	The thought that Jack is not a real person crosses my mind often.
SP4	Jack appears to be sentient (conscious and alive) to me.
SP5	I perceive Jack as being only a computerized image, not as a real person.
CP1	To what extent, if at all, did you have a sense of being with Jack?
CP2	Do you remember this as more like just interacting with a computer or with another person?
CP3	To what extent did you forget about Jack, and concentrate only on doing the task as if you were the only one involved?
CP4	To what extent was your experience in passing by Jack like that other real experience?
CP5	Overall rate the degree to which you had a sense that there was another human being interacting with you, rather than just a machine?
PH1	I felt as if Jack could walk through me.
PH2	I felt as if Jack could touch me.
PH3	I felt cautious when Jack was close to me.
PI	I felt Jack had the intelligence to avoid collisions.

Table 3. Summary of the ANOVA results for the three factors (obstacle type, obstacle behavior, and view condition) for the behavioral measures.

Factor	*Passing Distance*			*Walking Speed*			*Trajectory Length*			*Head Motion*			*Observation Ratio*		
	F	p	η_p^2	F	p	η_p^2	F	p	η_p^2	F	p	η_p^2	F	p	η_p^2
Obstacle	19.72	**<.001**	.441	9.58	**.005**	.277	7.66	**.010**	.234	11.97	**.002**	.277	5.91	**.023**	.191
Behavior	23.01	**<.001**	.480	35.18	**<.001**	.590	17.84	**<.001**	.420	.26	.662	.590	132.15	**<.001**	.840
View	8.18	**.008**	.247	26.64	**<.001**	.516	.062	.805	.002	7.13	**.013**	.516	3.86	.061	.134
Obstacle:Behavior	6.61	**.010**	.209	2.01	.162	.074	4.91	**.028**	.164	1.65	.209	.074	4.59	**.027**	.155
Obstacle:View	1.21	.280	.046	.39	.541	.015	7.20	**.013**	.224	.33	.572	.015	.002	.965	.000
Behavior:View	1.99	.148	.074	.03	.952	.001	7.66	**.010**	.234	1.43	.249	.001	6.46	**.003**	.205

4.1 Behavioral Measures

Figure 6 shows the averaged paths pooled over all participant trajectories in the different experimental conditions. Figure 7 shows the means and 95% confidence intervals for the three factors (obstacle type, obstacle behavior, and view condition) for the five behavioral measures.

We found no significant differences between the paths when participants walked back or forth on the platform, as well as no lateral preference effects, so we pooled the responses. We analyzed the results with repeated-measures ANOVAs and Tukey multiple comparisons with Bonferroni correction at the 5% significance level. We confirmed the normality with Shapiro-Wilk tests at the 5% level and QQ plots. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity when Mauchly's test indicated that the assumption of sphericity had been violated.

4.1.1 Passing Distance

We found a significant main effect of each of the three factors (obstacle type, obstacle behavior, and view condition) on passing distance (see Table 3). Pairwise comparisons revealed that participants kept a significantly larger distance from the obstacle when the view was restricted. Moreover, participants kept a significantly larger distance from the VH than from the RH. This result in AR is in line with a similar effect found in an immersive virtual environment by Argelaguet et al. [2]. Regarding the effect of behavior, for both obstacle types, the passing distance significantly increased monotonically in the order of standing, jumping, and walking. However, the magnitude in the increase from standing to jumping was more drastic with the VH than with the RH (see Figs. 7(a) and 7(b)).

4.1.2 Walking Speed

Again, we found a significant main effect of each of the three factors (obstacle type, obstacle behavior, and view condition) on walking speed (see Table 3). Pairwise comparisons revealed that participants significantly decreased their walking speed in the restricted view condition, which is supported by results in [50, 51]. Also, participants walked significantly slower when passing the VH compared to the RH for all behaviors, which extends previous results found only for stationary obstacles in [2]. Regarding the obstacle behavior, participants did not change their walking speed for those obstacles that remained in a fixed position, i.e., in the standing and jumping conditions. However, they significantly slowed down for the moving obstacle, i.e., the walking condition, compared to the other behaviors. We have to point out that passing distance and trajectory length were also increased from standing to jumping. This favor of changing walking direction for non-moving obstacles and changing walking speed for moving obstacles may be explained by behavioral mechanisms as discussed in [36].

4.1.3 Trajectory Length

Here, we found a significant main effect of obstacle type and behavior on trajectory length (see Table 3). We found significant two-way interaction effects between each two of the three factors (obstacle type, obstacle behavior, and view condition). Further tests performed for each obstacle type separately showed that the view condition still had a significant effect on trajectory length for RH, $F(1,25) = 8.35, p < .01, \eta_p^2 = .25$, but not for VH, $F(1,25) = 3.21, p > .05, \eta_p^2 = .11$; and multiple comparison with Bonferroni correction showed a significant increase from standing to jumping, and from standing to walking (see Fig. 7(d)). However, in the ANOVAs performed for each combination of obstacle type and view condition, the difference between standing and walking was not significant (only) in the restricted view condition with the VH obstacle, implying that participants tried to not change their path. Note that the slowest walking speed was also found in this combination of restricted view with VH obstacle.

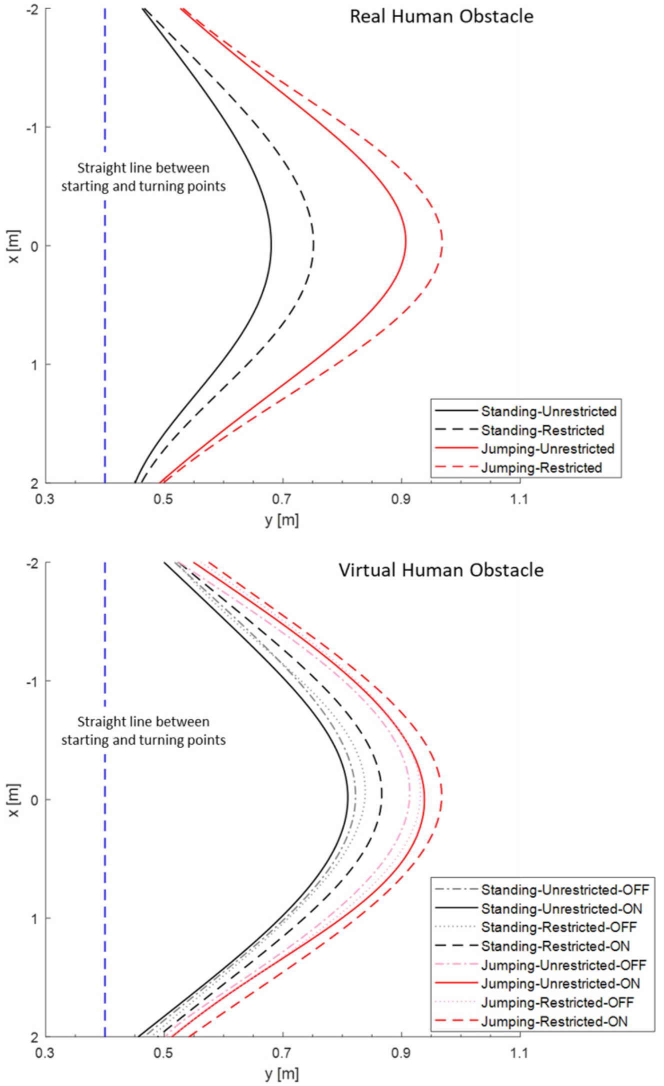

Fig. 6. Plot of the averaged paths pooled over all participant trajectories in the different experimental conditions for real human obstacle (top) and virtual human obstacle (bottom). In both plots, the obstacle was located at position $(0,0)$.

4.1.4 Head Motion

We found a significant main effect of obstacle type and view condition on head motion (see Table 3). Restricting the peripheral view on the HoloLens increased head motion, which is similar to the result reported for a helmet-mounted display in [17]. Participants moved their head significantly more in the presence of the VH compared to the RH. Further tests performed separately for each obstacle type revealed that the view condition did not have a significant effect on the participants' head motion for the VH, $F(1,25) = .99, p > .05, \eta_p^2 = .04$, while it had a significant effect for the RH, $F(1,25) = 9.87, p < .01, \eta_p^2 = .28$. Pairwise comparisons between behaviors revealed significant differences only in the combination of unrestricted view with the RH between all behaviors. Head motion was significantly increased in order of standing, jumping, and walking. We found no significant difference between behaviors in all other combinations of obstacle type and view condition (see Fig. 7(e)).

4.1.5 Observation Ratio

We found a significant main effect of obstacle type and behavior on observation ratio (see Table 3). We also found significant interactions between obstacle type and behavior, and between view condition and behavior. Participants observed the VH more than the RH for all behaviors. However, the increase in walking was more striking compared to the other two behaviors (see Fig. 7(f)). Regarding the view condition, there was a nonsignificant trend ($p < .061$) of participants observing the obstacle more when the view was restricted, but for the walking obstacle, the observation ratio was similar in both view conditions.

4.1.6 Effects of Vibration

Due to the partial factorial design, we analyzed the vibration factor separately from the three factors (obstacle type, obstacle behavior, and view condition) as it applies only to the VH conditions. To consider the effects of vibration on locomotion behavior, we performed repeated-measures ANOVAs for the vibration condition for each combination of obstacle behavior and view condition. For the standing behavior, we did not find any significant effect of vibration in the unrestricted view condition. However, in the restricted view condition, there was a nonsignificant trend indicatively that participants kept a larger distance when they felt the vibrations ($M = .831$ m) compared when vibrations were absent ($M = .795$ m), $F(1,25) = 4.1, p = .054, \eta_p^2 = .14$ (see Fig. 6). For the jumping behavior, in the unrestricted view condition, walking speed was significantly slower with vibrations ($M = .982$ m/s) than without ($M = 1.0$ m/s), $F(1,25) = 4.31, p < .05, \eta_p^2 = .15$ (see Fig. 8(a)). On the other hand, in the restricted view condition, we found a nonsignificant trend that participants kept a larger distance with the vibrations ($M = .94$ m) compared to without ($M = .9$ m), $F(1,25) = 3.39, p = .077, \eta_p^2 = .12$ (see Fig. 6). We observed a nonsignificant trend for the increase in observation ratio with vibrations ($M = .21$) compared to without ($M = .15$), $F(1,25) = 3.46, p = .075, \eta_p^2 = .12$. For the walking behavior, there was a significant effect of vibration on walking speed, $F(1,25) = 6.96, p < .05, \eta_p^2 = .22$, in the unrestricted view condition; participants walked significantly slower when they felt the vibration caused by the VH's footsteps ($M = .88$ m/s) than when they did not ($M = .91$ m/s). These behavioral effects in AR extend and support previous research by Lee et al. [33] focusing on subjective effects of footstep vibrations in VR.

4.2 Subjective Measures

For the subjective measures, we decided to use parametric statistical tests to analyze the questionnaire responses in line with the ongoing discussion in the field of psychology indicating that parametric statistics can be a valid and often more expressive method for the analysis of ordinal data measured by experimental questionnaires [29, 32]. In agreement with this approach, the data did not fail the Shapiro-Wilk test at the 5% level for normally distributed data. We performed a paired t-test for the SSQ scores. We found no significant difference between pre ($M = 12.8, SD = 26.0$) and post ($M = 16.5, SD = 35.8$) SSQ scores, $t(25) = 1.06, p = .29$. We analyzed the other subjective measures with repeated-measures ANOVAs and Tukey multiple comparisons with Bonferroni correction at the 5% significance level. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity when Mauchly's test indicated that the assumption of sphericity had been violated.

For social presence, we computed the mean for ratings from SP1 to SP5 (see Table 2) with inverted scores for SP3 and SP5 (Cronbach's $\alpha = .761$). A higher social presence score indicates that participants estimated the VH as more conscious and aware [5]. Our results showed no significant main effects of view condition, $F(1,25) = .52, p > .05, \eta_p^2 = .02$, or vibration, $F(1,25) = 2.65, p > .05, \eta_p^2 = .096$ (see Fig. 8(b)).

For co-presence, we also averaged ratings from CP1 to CP5 (Cronbach's $\alpha = .792$). A higher score means that participants reported a stronger sense of being together with the VH. The results indicate that there was a significant main effect of vibration on co-presence, $F(1,25) = 9.69, p < .01, \eta_p^2 = .28$. We found no significant main effect of view condition, $F(1,25) = 1.59, p > .05, \eta_p^2 = .06$, nor did we find an interaction effect between view and vibration conditions, $F(1,25) = .35, p > .05, \eta_p^2 = .01$, on co-presence (see Fig. 8(b)). Post-hoc tests indicated that participants rated higher scores in the vibration ON ($M = 4.91$) than OFF ($M = 4.42$) conditions, $p < .01$; and the unrestricted view with vibration OFF ($M = 4.28$) was significantly lower rated than the other three combinations.

For the remaining questions, we performed the statistics for each measure. For PH1, ratings were inverted for consistency with the rest of the questions. For the perceived physicality of the VH (i.e., PH1, PH2, PH3) we found a significant main effect of vibration; F statistics for each question were as follows: $F(1,25) = 4.8, \eta_p^2 = .16$, $F(1,25) = 4.33, \eta_p^2 = .15$, $F(1,25) = 5.82, \eta_p^2 = .19$, with $p < .05$ for all. We found no significant main effect of view condition and interaction between view and vibration for all questions. Post-hoc tests indicated that for PH1, participants felt the VH was more physical (as opposed to phantasmal) when they felt vibrations synced with the VH's behavior ($M = 3.27$) compared to the non-vibration condition ($M = 2.94$). For PH2, participants rated the VH's ability to physically affect them higher in the vibration ON condition ($M = 2.9$) compared to the vibration OFF condition ($M = 2.5$). For PH3, participants felt more cautious for vibration ON ($M = 4.35$) than for vibration OFF ($M = 4$). We also found a main effect of vibration, $F(1,25) = 4.8, p < .05, \eta_p^2 = .16$, on the perceived intelligence (PI) level of the VH. Interestingly, post-hoc tests indicated that participants who felt the vibration rated the VH's intelligence level as higher ($M = 2.5$) than those who did not feel the vibration ($M = 2.17$) (see Fig. 8(c)).

5 Discussion

In this section, we discuss the behavioral and subjective results of the experiment, potential explanations, and implications. In general, the locomotion behavior participants exhibited in our study is affected by proxemics, obstacle avoidance, and motor behavior, as it involved interpersonal space, awareness of the surroundings, and motion planning. In proxemics, one's invisible boundaries can expand or contract depending on one's characteristics and physical activity [19]. Therefore, participants may have planned their motion—route and speed—in consideration of the expanded or contracted obstacle's boundary and surroundings. Whether the obstacle was real or virtual, in this regard, would primarily affect the initial size of the boundary. A more active behavior of the obstacle would thus result in an expansion. On the other hand, the view conditions with restricted or unrestricted periphery would primarily have effects on the participants' awareness of the surroundings and the position or motion of the obstacle. In the following sections, we discuss each factor in the experiment in detail.

5.1 Effects of Obstacle Type

Our results showed that participants stayed significantly farther away and walked a longer path at a slower speed around the VH than the RH, while looking more often towards the VH than the RH. Overall, our results provide strong support for Hypothesis H1. One possible expla-

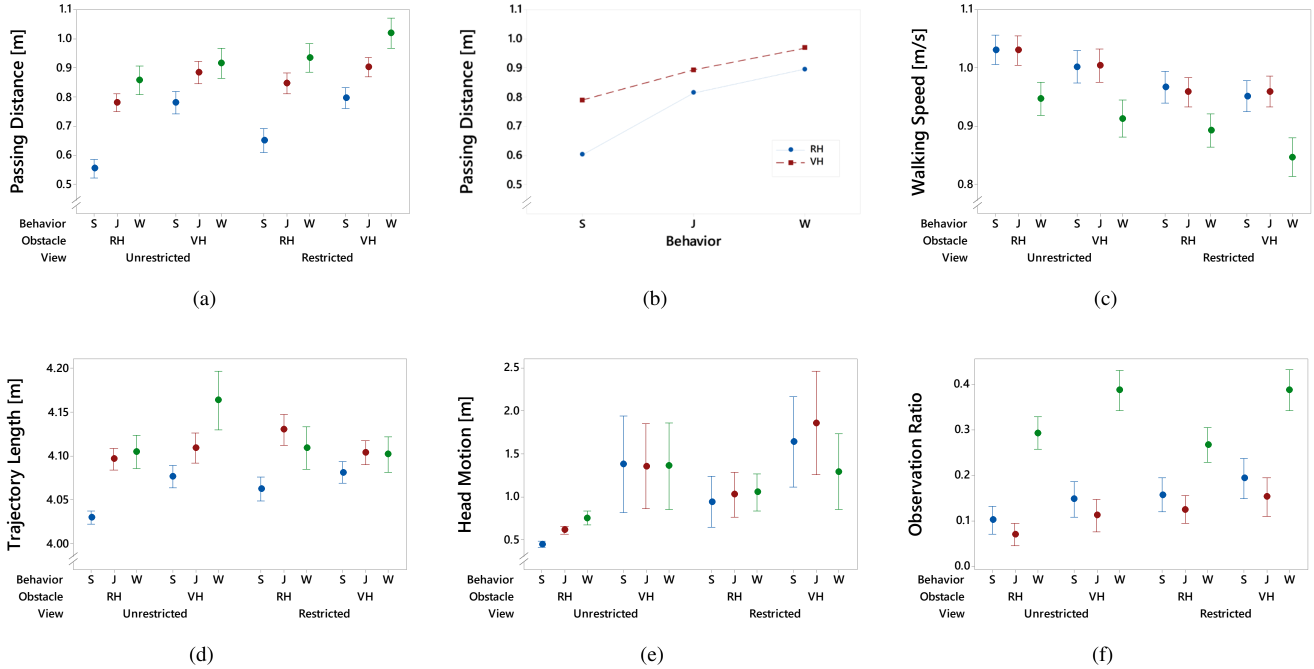

Fig. 7. Results of the behavioral measures in the different conditions showing the means and 95% confidence intervals: (a) passing distance, (b) interaction between obstacle type and obstacle behavior for passing distance, (c) walking speed, (d) trajectory length, (e) head motion, and (f) observation ratio.

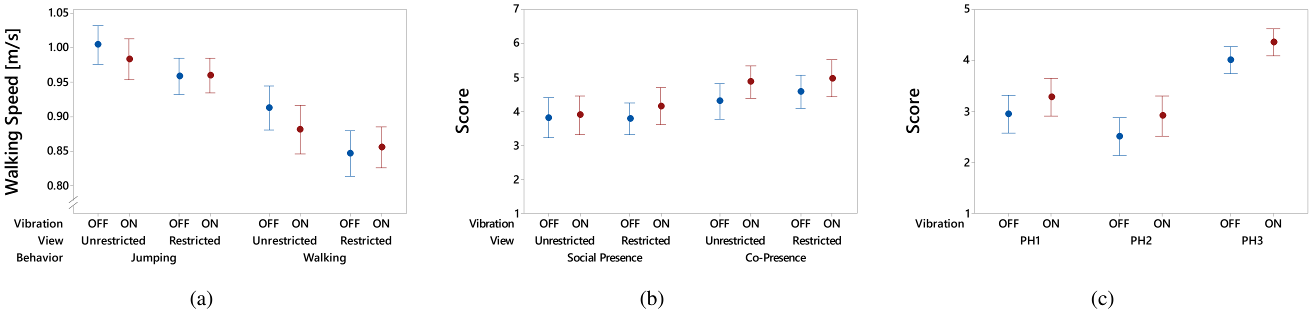

Fig. 8. Results of the behavioral measures for the vibration in jumping and walking behavior with (a) interval plot of the walking speed and results of the subjective measures for the vibration and view conditions with (b) interval plot of social presence and co-presence, and (c) interval plot of the remaining questions PH1, PH2, PH3, and PI. The plots show the means and 95% confidence intervals.

nation for this effect is that the VH did not appear to be a social entity that obeys social norms to the same level as the RH could be expected to. The moderate social presence and perceived intelligence scores suggest that participants had lower social expectations for the VH. These lower expectations of social behavior may thus result in the expectation that the VH may behave in unpredictable ways, such that participants increased their clearance distance, showed increased observation time, and decreased their walking speed. We received multiple comments by our participants that seem to support this interpretation. For instance, one participant stated, *"I was more focused on the virtual human [..] because I don't interact with a virtual human as much,"* and another participant said, *"[..] he would not change the course of direction in order to not run into me."* Interestingly, these differences between the VH and RH were less prominent in the more active behavior of the human obstacles, i.e., when they were jumping or walking, which may have made it easier for participants to predict their future behavior.

5.2 Effects of Obstacle Behavior

Regarding the effects of the real or virtual human obstacle's behavior, understanding what was changed between the behaviors is important. From standing to jumping, the obstacle's invisible boundary would have been increased due to the increased activity, but behavioral uncertainty would have been reduced as the obstacle repeated its jumping behavior in a loop. The observed increase in passing distance and the decrease in observation ratio supports this interpretation. In both of these behaviors, the location of the obstacle has not changed. Therefore, participants could focus less on tracking the obstacle and avoid the collision by simply changing their route with a greater clearance distance. Changing the walking speed would not have been necessary for this case as there was no additional uncertainty of the obstacle's behavior, as discussed in [36]. However, if the obstacle is actively walking, participants have to divide their attention to track the obstacle, maintain spatial awareness, and predict a safe route based on the current movement of oneself and the obstacle to avoid a collision while reaching the goal position. Due to this increased mental load, one may reduce the walking speed and look more towards the obstacle. Our results clearly show the decrease in walking speed and the increase in observation ratio, and these changes were the same regardless of the obstacle type. For the walking obstacle, participants would have needed to dynamically adjust their motion—direction and speed—to avoid collision, resulting in a more irregular path trajectory. The increased variances in walking speed and trajectory length support this assumption. Regarding the obstacle behavior, we logged comments in this scope such as, *"Jumping made me walk around more, and walking made me pause and wait,"* as well as, *"Jumping [was] least alarming because it was predictable; standing could become walking at any moment."*

5.3 Effects of View Condition

With respect to our Hypothesis H2, we expected that participants would need to look around more in the restricted view condition to have a confident level of spatial awareness, and would walk slower as the uncertainty of the surroundings increased. Our results support this hypothesis and showed these significant changes in head motion and walking speed regardless of obstacle type. However, when it comes to the awareness of obstacle position, which is an important factor for collision avoidance behavior, the view condition affects the locomotion behavior in ways that are further complicated by the other factors. For the unrestricted view condition, participants could have kept both awareness of the RH obstacle and the surroundings with less head motion as the RH was still visible when they looked around (see the low variation for RH-U in Fig. 7(e)), while for the VH, participants should have kept turning back to the probable location of the VH to reduce uncertainty, and this process—mental demand and behavioral restriction—of obstacle tracking in the VH condition might reduce one's spatial awareness due to the limited cognitive capacity and behavioral constraint. Hence, differences in locomotion behavior between the RH and VH obstacles in the unrestricted view condition would be mostly due to the limited augmented area. On the other hand, in the restricted view condition, head motion to gain spatial awareness would have affected obstacle position tracking in the same way (increasing uncertainty of the obstacle position) for both the RH and VH. Our results for passing distance, trajectory length, head motion, and observation ratio support this interpretation and Hypothesis H3.

Regarding the subjective responses, we expected that the view condition would have an effect on the participants' perception of the VH, which may explain some of the effects on the locomotion behavior. In particular, we initially expected that social presence and co-presence would increase for the restricted compared to the unrestricted view condition. The rationale behind this expectation was that the progressive disappearance in the unaugmented area when looking at the VH would reinforce one's belief that this obstacle is not real. Therefore, by removing this reinforcement, we would see the increase (as less decreased) in the related subjective measures. However, our subjective responses did not show significant effects in support of this Hypothesis H5, although we received multiple comments to this effect. For instance, participants commented, *"I felt Jack is more real with restricted view,"* and, *"Restricted view did make the experience slightly more realistic and harder,"* but also, *"I preferred the unrestricted view because it was easier for me to see where I was going."*

5.4 Effects of Vibrotactile Feedback

We expected that vibrotactile feedback would have an effect on the participants' perception of the VH and, therefore, would have indirect effects on the locomotion behavior. In particular, we assumed that social presence and co-presence would increase when vibrotactile footstep feedback was provided for the VH. We assumed that this effect would be related to expectancy violations. That is, participants knew that the obstacle was virtual, and they would not expect such vibrations to be caused by the VH. Therefore, when they felt the vibration, their expectation would be violated in favor of a higher regard for the VH. Indeed, we found that footstep vibrations synced with the VH's behavior significantly increased co-presence and perceived physicality of the VH, thus supporting H6. We also received multiple informal comments by our participants to this respect, such as, *"The floor vibration made both the jumping and walking virtual human seem more real, and made me especially nervous when the virtual human was walking towards me,"* and, *"Vibration made more impact on believing it's real."* In addition, vibrations also affected participants' locomotion behavior. However, we only found significant effects for the unrestricted view condition, for which vibrations decreased walking speed in jumping and walking behavior, causing a larger deviation from locomotion behavior shown with the RH, which does not match with Hypothesis H4. It is interesting that the benefits of vibrotactile footstep feedback thus mainly seem to lie in subjective estimates rather than in objective locomotion behavior, considering the opposite results in the view condition. This implies some behavioral responses toward a VH may not be affected by a user's subjective perception of the VH, emphasizing the use of both subjective and behavioral measures.

6 Conclusion and Future Work

In this paper, we presented, to the best of our knowledge, the first study investigating factors and issues related to human locomotion behavior and proxemics in the presence of a virtual human in AR.

First, we discussed a unique issue with current-state optical see-through HMDs, namely the mismatch between a small augmented visual field and a large unaugmented periphery, and its potential impact on locomotion behavior in close proximity of a virtual human. We discussed a potential simple solution based on restricting the field of view to the central region, and we presented the results of a controlled user study, which revealed objective benefits to this approach by producing behaviors that more closely matched those observed when seeing a real human, but also showed an overall limited acceptance of restricting the field of view from responses during the post-experiment interview.

Second, we discussed the limited multimodal feedback provided by virtual humans in AR, presented a potential improvement based on the work by Lee et al. [33] that used vibrotactile feedback induced via the floor to induce realistic proxemic behavior in VR. While in VR benefits of such vibrations appeared in both subjective and objective responses, we found in our AR setting that benefits are less visible in objective locomotion behavior than in subjective estimates of co-presence.

Third, we investigated and documented significant differences in the effects that real and virtual humans have on locomotion behavior in AR with respect to clearance distances, walking speed, and head motions. We discussed potential explanations for these effects related to social expectations, and analyzed effects of different types of behaviors including idle standing, jumping, and walking that real or virtual humans may exhibit in the presence of an observer.

We believe that investigating behavioral and perceptual differences induced by these technological and social factors in AR is important for practitioners and researchers aiming to further bridge the gap between real and virtual humans in shared spaces. In future work, we plan to extend our studies to a larger augmented field of view that is simulated using an immersive virtual environment to predict the effects that future AR displays might induce on proximal behavior with virtual humans. We also plan to explore other multimodal cues to compensate for limited visibility in AR. Regarding social factors, investigating situations where multiple real and/or virtual humans are involved in a shared environment may give useful insights into real-life situations. In such cases, gender and cultural effects should also be more carefully considered.

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