Virtual Shadows for Real Humans in a CAVE: Influence on Virtual Embodiment and 3D Interaction

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ABSTRACT

In immersive projection systems (IPS), the presence of the user's real body limits the possibility to elicit a virtual body ownership illusion. But, is it still possible to embody someone else in an IPS even though the users are aware of their real body? In order to study this question, we propose to consider using a virtual shadow in the IPS, which can be similar or different from the real user's morphology. We have conducted an experiment (N=27) to study the users' sense of embodiment whenever a virtual shadow was or was not present. Participants had to perform a 3D positioning task in which accuracy was the main requirement. The results showed that users widely accepted their virtual shadow (agency and ownership) and felt more comfortable when interacting with it (compare to no virtual shadow). Yet, due to the awareness of their real body, the users have less acceptance of the virtual shadow whenever the shadow gender differs from their own. Furthermore, the results showed that virtual shadows increase the users' spatial perception of the virtual environment by decreasing the inter-penetrations between the user and the virtual objects. Taken together, our results promote the use of dynamic and realistic virtual shadows in IPS and pave the way for further studies on "virtual shadow ownership" illusion.

CCS CONCEPTS

• **Human-centered computing** → User studies; Virtual reality;

KEYWORDS

virtual reality, shadows, embodiment, 3D interaction

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1 INTRODUCTION

Shadows are paramount in our everyday life as they provide information about depth, proximity, or shape of our environment [Puerta 1989]. Given their relevance, since their beginning, virtual and mixed realities research have focused in the simulation of virtual shadows in order to reach a more accurate representation of the reality [Thompson et al. 2016]. One particular shadow is the one cast by our own body which in combination with a virtual avatar can reinforce the user's virtual experience [Slater et al. 1995] and theoretically it can also enhance spatial perception. However, the user's avatar representation is way harder to introduce in Immersive Projection Systems (IPS) such as CAVE displays [Cruz-Neira et al. 1993]. Indeed in projective displays the users are equipped with stereoscopic glasses and they are able to see their own body. Such configuration makes it harder for the user to embody someone else since they are always aware of their real body.

Figure 1: Participants interacting in a virtual environment inside a CAVE system. They can embody a male (left) or a female (right) virtual character.

In this paper we propose to study the influence of the user's virtual and dynamic shadow in a VR CAVE display. Is it possible to embody someone else in a CAVE environment even though the users are aware of their own body? Does the virtual shadow influence their interaction behavior? In order to answer these questions we carried out an experiment in order to assess the user's virtual embodiment and the user's 3D performance in presence of a virtual shadow. The virtual shadows enabled to provide a virtual representation of the user which differed from their own physical body even though they were still able to see their body. In particular, we studied how the users appropriate different virtual shadows (male and female shadow) and how does the virtual shadow affects the user behavior when performing a 3D positioning task. The results showed that the shadow can have an influence on the user's behavior while interacting, and that participants seemed to prefer virtual shadows which were closer to their own body.

In the remainder of this paper we first make an overview of previous work that has been done on adding user shadows in VR environment. Second we describe the experiment that aims to study the influence of virtual shadows on the user comfort and presence and on the environment understanding. Third we present the results of the experiment. The paper ends with a discussion.

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2 RELATED WORK

Increasing the embodiment of the users in virtual reality applications has been studied in a number of different works. Although the majority of works have been focusing on the user's avatar [Kilteni et al. 2012], several works have also addressed the use of virtual shadows to reinforce the effect. For example, [Slater et al. 1995] carried out a study on the influence of the presence of shadows in HMD virtual environment. They did not find any influence of the shadows on depth perception but they found that adding a static shadow increases the user presence and that adding a dynamic shadow increases it even more. This study focused on the object shadows and no user dynamic shadow was considered. In later work they introduced the dynamic shadow of the user in HMD to confirm that the realism of the scene has an impact on the user behavior [Slater et al. 2009]. Even though users virtual shadows have not been widely studied, avatars are commonly used in virtual reality HMDs. There even were studies on the influence of the morphology of the virtual avatar on the user behavior and embodiment in HMD [Peck et al. 2018]. Nevertheless they did not carry out any study on immersive projection systems.

Indeed using avatars in IPS or screen displays can be harder since the users are aware of their own body. When using such systems, casting shadows can still be a solution to enhance the user experience. Even though, in 1995, Slater et al. did not find any influence of the shadows on depth cue, later studies [Hubona et al. 1999] found out that when using screen displays adding objects shadows increases the accuracy during positioning tasks. However the study focused on the object shadows and no user shadow was considered. Moreover the study was carried out on screen displays that do not provide any immersion. Such results were confirmed in later studies carried out on augmented reality displays [Diaz et al. 2017; Sugano et al. 2003]. Adding shadows to the virtual objects integrated in the real world increases the objects presence and provides depth cues that increase the spatial perception. [Hu et al. 2000] also confirmed the results in VR HMD. Regarding the user shadow, altering the shadow behavior compared to the user's body behavior can modify the user perception of the environment. [Ban et al. 2015] carried out a study where the shadow was more or less independent from the user. The shadow was then able to move differently from the user movement. The users were then confused and were not always able to tell if they or their shadow were moving. Moreover their movement were altered by the shadow movements. Such study was carried out by projecting shadows on a wall but no virtual reality environment nor interaction were considered.

[Steinicke et al. 2005] were the first ones to introduce user shadows on IPS. They added the presence of users' virtual shadows and reflections on a responsive workbench. The real reflection of the user (captured with a camera) was added on a metallic surface and a virtual shadow of the user's hand was cast on the same surface. The authors claim that it increases the realism of virtual objects but no study was made to evaluate how this approach increases users perception and improves objects interaction. More recent work from [Yu et al. 2012] proposed to increase the realism of virtual environments in CAVE displays. They confirmed that the user presence was increased when having shadows and reflections that corresponded to the users' body movements. The body movements were forced by the application and the task consisted in naturally walking in the display to avoid a collision with a virtual character. Nevertheless no complex 3D interaction task was proposed to study the influence on depth perception. Later work from [Kwon et al. 2015] enhanced wall-sized VR application by adding objects shadows on the real floor in front of the display. They carried out a study were users had to touch the virtual objects with a direct touch metaphor. Their results suggested that the shadow cue is even more important than the stereoscopic cue. Regarding the shadow of the user, no study was considered.

According to the previous work, and to the best of authors knowledge adding user shadows in a CAVE while performing complex 3D interaction task has not been studied yet. Thus we propose to study, for the first time, the influence of the presence and the morphology of the user's virtual shadow on the virtual embodiment and on a complex 3D interaction task in a CAVE display.

3 EXPERIMENT: INFLUENCE OF THE VIRTUAL SHADOWS ON VIRTUAL EMBODIMENT AND 3D INTERACTION

In this experiment, our goal is to study the influence of a virtual shadow on the presence, the embodiment and the precision of the participants when performing a 3D interaction in an IPS, a CAVE display. We designed a 3D positioning task in which participants had to place a physical ball over virtual targets placed on planar surfaces, such as tables or walls. The goal of the positioning task was to place the ball as close as possible to the target areas without going through them. During the experiment the participants were presented with three virtual shadow conditions: A male shadow, a female shadow and no shadow. We hypothesized that the ability to see their virtual shadow can influence both the user's perception on their shadow but also on the way they perceive and interact in the virtual environment, thus, two main research questions were addressed:

- **Q1**: Is it possible to embody someone else in an IPS even though the users are aware of their own body?
- **Q2**: Does a user's virtual shadow increases the user's spatial perception of the virtual environment in an IPS?

3.1 Apparatus

Participants were immersed in the virtual environment using a 9.6×2.9×3.1 meters CAVE display. The CAVE system is built with 4 screens: one on the floor, one on the front and one on each side. The projection on the screens is made using Barco F90-4K13 laser projectors. Every screen but the floor is back-projected. The tracking data is provided by an infrared optical tracking system from Optitrack[1]. The optical tracking is composed of 12 cameras (4 Optitrack Prime 13W and 8 Optitrack Prime 13).

The dynamic virtual shadow is created from a virtual 3D model of a humanoid. For the purpose of the experiment we chose to have a male and a female 3D model (see Figure 2). Such models have been chosen to fit the human proportions and to relieve the experiment from a cumbersome calibration process. Thus the matching between

[1]Optitrack tracking hardware http://optitrack.com/hardware/

both the virtual and the real body are simply made by scaling the model so that its height corresponds to the participant's height.

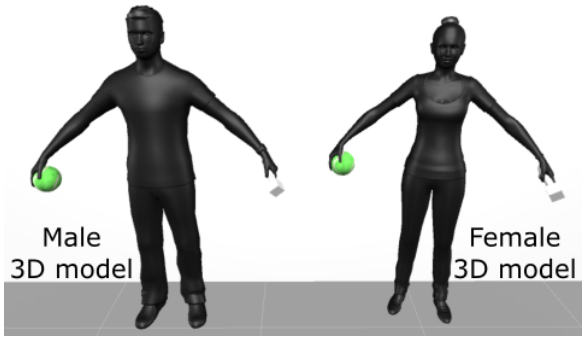

Figure 2: 3D models — Two models were used to cast a virtual shadow in the virtual environments : a male model (left) and a female model (right).

Regarding the dynamic part of the shadow, an inverse kinematics (IK) algorithm was used to provide movement to the shadow and to make its position correspond to the user's one. The Final IK[2] Unity asset was used to optimize the position of the rigged models to fit the actual position of the user. The Final IK algorithms were able to converge to an optimized solution by providing the position of both feet, both hands and the head of the user. Thus, participants were equipped with tracking devices on the feet, hands and head (see Figure 3-left). Finally due to experimental testing we noticed that providing the orientation of the pelvis to the IK algorithm gave better visual performances. Thus the user was also equipped with an additional tracking marker in the waist to track the pelvis. To simplify the experiment and the recorded data, a physical ball was placed on the participants right hand as an extension of their arm and body. A controller was hold on their left hand (see Figure 3-right). The 3D model that matches the user position is introduced in the virtual environment but no rendering of the model's mesh was done, only the cast shadow is displayed.

Since the ball was not perfectly rigidly attached to its tracking constellation and that the participants were able to grab it as they wanted to, a calibration step was introduced during the experiment. The calibration step aimed to compute the distance between the physical ball and the virtual ball (used to cast the ball shadow). The participants were asked to place 3 times the physical ball over a physical table whose height was perfectly known (see Figure 4). Then the offset between the physical and virtual balls was computed and used to correct the recorded data. The calibration step was performed at the beginning and at the end of each experimental condition.

Regarding the lighting of the scene we chose to use 3 directional lights to provide the participants with 3 virtual shadows of themselves. Two lights were oriented of around 45° according to the wall normal vector and one light was almost collinear with the wall normal. Such lighting configurations provided the scene with two shadows cast half on the floor and half on the wall and one shadow that is almost only cast on the wall (see Figure 5). The VR

[2]Final IK asset http://www.root-motion.com/final-ik.html

Figure 3: Tracking devices — Six infrared constellations (red) were placed over the participants (left) to provide tracking data to perform the inverse kinematics optimization. A ball was placed in their right hand, as an extension of their arm, and a controller in their left one (right).

Figure 4: Calibration step — The calibration step enables to compute the offset between the physical ball and the virtual ball at the beginning and end of each virtual shadow condition (N, F or M).

application was developed using Unity 5.6.1f and ran at an average frame rate of 60 fps.

3.2 Participants

27 participants from the university campus took part in the experiment (Age: min = 23, max = 55, and avg = 31 ± 8), recruited both among general students and staff. For the purpose of the experiment we chose to recruit 14 women and 13 men since the participant were confronted to a male and a female shadow. Participants were recruited asking for minimal previous experience in VR: 18 subjects had none to very limited previous experience with virtual reality, 7 had some previous experience, and only 2 were familiar with VR. None of the participants knew about the experiment being tested, or that they would be presented with virtual shadows. All participants were right-handed since the ball was placed in their right hand for the positioning task.

3.3 Experimental Task

Participants were asked to position a physical ball (7cm radius, see Figure 3-right) over circular green target areas (2.5cm radius). The target areas were positioned over 2 virtual tables and a virtual

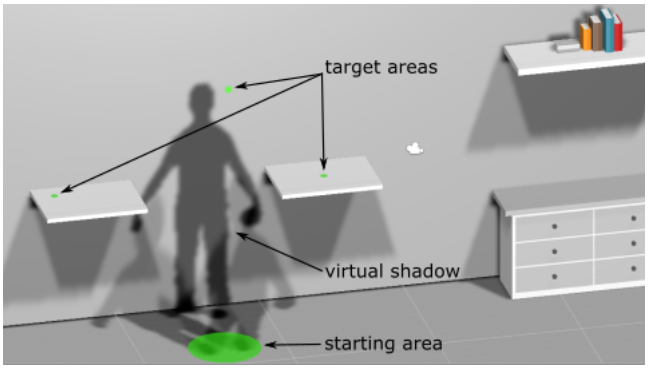

Figure 5: Virtual environment of the experiment. Users were asked to place the physical ball over the green target areas that were displayed on both tables and on the wall. Three different point lights generated three different virtual shadows at the same time.

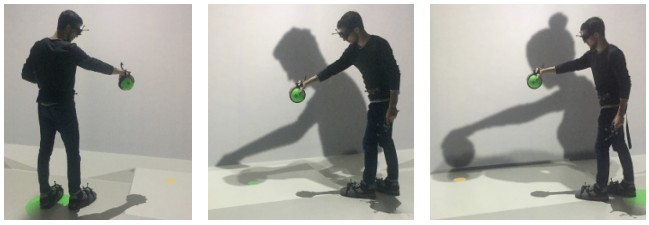

Figure 6: Virtual shadow conditions — The participants performed the positioning task with 3 different virtual shadow conditions: None (N) (left), Male (M) (middle), Female (F) (right). The real shadow of the user is visible on the floor but does not match the natural behavior of a shadow in the virtual environment and is not taken into consideration.

wall (Figure 5). Only one circular target was displayed at a time in order to help the user know which target he/she had to focus on. Every run of the experiment started with a target on the left table, then a target on the wall and then a target on the right table and so on. Once participants were satisfied with the placement of the target, they had to validate the positioning of the ball by pressing the trigger of the controller placed on their left hand (see Figure 3-right). In order to reduce the required time to perform a timer was added. The timer was depicted by changing the color of the current target area. The target areas appeared green, they went orange after 3 seconds and red after 6. Participants were asked to try and validate the positioning of the ball before the target became red. Nevertheless they were told to be as accurate as possible even if they had to spend more time for each target.

In order to decrease learning effects, participants had to face a different number of target configurations. Three target positions were defined for each table and for the wall. Moreover the tables were positioned at a variable height (90cm or 110 cm).

3.4 Experimental Protocol

An informed consent form was signed by each participant before starting the experiment. The form stated the participants' right to withdraw and presented the experiment and the main goal of the research. In addition, it also asked their consent regarding image and video copyright. In order to minimize the priming of participants, little details were provided regarding the purpose of the shadow. Mainly, participants were told that the experiment aimed to assess people precision when performing 3D positioning tasks. They were also told that the virtual shadow conditions of the scene could vary but no additional details about the shadows were given.

The experiment was divided into 3 blocks. During each block the participants were presented with one virtual shadow condition which was either No shadow (N), Male shadow (M) or Female shadow (F) (see Figure 6). Each participant performed entirely the positioning task for each one of the 3 conditions.

Considering all possible target combinations, three targets (wall, left table, right table), two heights and three positions, participants had to perform the placement task 18 times for each condition. Moreover, as three repetitions were considered, each block resulted in 54 trials. Finally, a training period of half a run (9 targets) was present at the beginning of each block. To counterbalance the influence of the running order of the conditions on the participants behavior, the participants were divided into 6 groups (M/F/N, M/N/F, F/M/N, F/N/M, N/M/F and N/F/M). Each group was composed of at least 2 male and 2 female participants.

After each block participants were asked to fill in a subjective questionnaire (see Table 1) in order to evaluate their subjective appreciation of the experiment and collect their feedback. The questionnaires began with 5 question to evaluate the presence of the user following the suggestions of Usoh et al. [Usoh et al. 2000]. Then there were questions regarding the ownership and some questions about the task and the user comfort. Finally the participants were free to comment their strategy to perform the task and to detail their feelings and comments in presence or absence of a shadow.

While performing the positioning task the participants were immersed in the CAVE. After each condition the tracking constellations were removed and the users had to fill in the questionnaire on an independent laptop. Then they were reequipped with the tracking constellation and reintroduced in the CAVE. The whole experiment including the questionnaires lasted around 45 min in total (15 min per virtual shadow condition).

In addition to the subjective questionnaires assessments the following information was recorded for each positioning task:

- The depth error (Y axis for the tables and Z axis for the wall) between the ball and the target area when the position is validated by the participant. The error is positive when the ball is positioned over the surface and negative when its position inside the surface.
- The time the participant took to perform one positioning task. As the trials were performed sequentially, the task completion time matches the time between two validations.

Table 1: Summary of the subjective questionnaire. (P: Presence, SA: Shadow Appreciation, TA: Task Appreciation, O: Ownership, A: Agency)

ID	Question
P_1	I had a sense of "being there" in the virtual house living room space
P_2	There were times during the experience when the living room space was the reality for me
P_3	The living room space seems to me to be more like images that I saw or somewhere that I visited
P_4	I had a stronger sense of being elsewhere or being in the living room space
P_5	During the experience I often thought that I was really standing in the living room space
SA_1	When positioning the ball on the tables I felt that the virtual shadow was useful
SA_2	When positioning the ball on the wall I felt that the virtual shadow was useful
SA_3	I felt that the virtual shadow was a good indicator of the proximity of the ball with the tables
SA_4	I felt that the virtual shadow was a good indicator of the proximity of the ball with the wall
TA_1	I felt that I was accurate on positioning the ball
TA_2	I felt that the positioning of the ball was rather easy
O_1	I felt as if the virtual shadow was my own shadow
O_2	I felt as if the virtual shadow was from someone else's
A_1	I felt as if the virtual shadow moved just like I wanted
A_2	I expected the virtual shadow to react in the same way as my own body
A_3	I felt like I controlled the virtual shadow as if it was my own shadow

3.5 Results

During the analysis we explored the effect of the participants' gender on the results. If the gender did not significantly influenced the results, data was pooled. Regarding the ANOVA analysis, effect sizes are expressed using the partial eta squared (η_p^2). The general rules of thumb given by [Miles and Shevlin 2001] state that the qualifiers "small", "medium" and "large" correspond to cases where $\eta_p^2 > 0.01$, $\eta_p^2 > 0.06$ and $\eta_p^2 > 0.14$ respectively. Only significant effects are discussed. We first discuss performance measurements and then the subjective appreciations of participants.

3.5.1 Performance Measurements. The main indicators of task performance were the final depth position (see Figure 7) and the task completion time. We first analyzed the effect of the Shadow type and the Task on the depth error using a two-way ANOVA analysis considering participants as a random factor. The ANOVA analysis showed a main significant effect for Shadow [$F_{2,52} = 8.99$, $p < 0.001$, $\eta_p^2 = 0.25$] and Task [$F_{2,52} = 39.67$, $p < 0.001$, $\eta_p^2 = 0.60$], no interaction effect was found [$F_{4,104} = 0.26$, $p = 0.9$]. Tukey post-hoc tests showed that for the male shadow condition participants were more conservative while performing the task $M = 3.2cm$; $SD = 3cm$ compared to the female shadow $M = 1.4cm$; $SD = 3.3cm$ and without shadow $M = 0.9cm$; $SD = 3.7cm$. In general, in the condition without shadows participants were more prone to go through the target surface. On the contrary when a virtual shadow was present the user tend to stop their movement before going through the target surface. Regarding the Task, post-hoc tests show that participants were able to place the ball closer to the target for the Left table $M = 0.8cm$; $SD = 2.3cm$ and the Right table $M = 0.0$; $SD = 2.8cm$ compared to the Wall $M = 3.7cm$; $SD = 3.6cm$. The higher depth error for the wall condition can be explained by the fact that the wall was a flat homogeneous surface which did not provide enough depth cues.

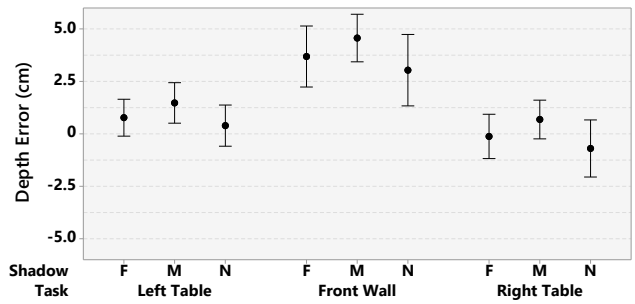

Figure 7: Mean interval plot (CI 95%) for the depth positioning error, grouped by the Virtual shadow condition and the Task.

Regarding the task completion time (see Figure 8), the ANOVA analysis showed a main effect on the Task [$F_{2,52} = 68.24$, $p < 0.001$, $\eta_p^2 = 0.72$] and an interaction effect [$F_{4,104} = 4.13$, $p < 0.01$, $\eta_p^2 = 0.13$], there was no effect on Shadow [$F_{2,52} = 0.72$, $p = 0.49$]. Tukey post-hoc tests showed that participants required significantly more time to perform the task in the Left table condition $M = 2.65s$; $SD = 0.51s$ compared to the Right table condition $M = 2.28s$; $SD = 0.49s$ and the Wall condition $M = 2.32s$; $SD = 0.48s$. This result can be explained by the fact that all participants were right handed and required more time to access the left table. Post-hoc tests were not conclusive for the interaction effect.

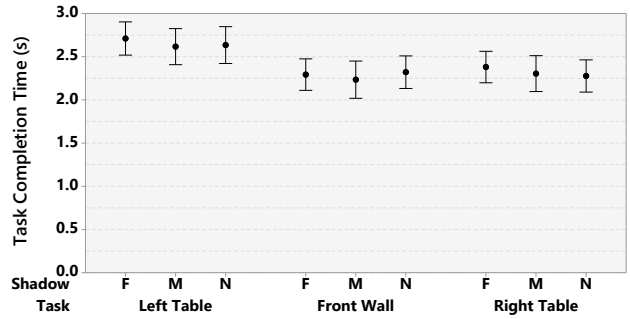

Figure 8: Mean interval plot (CI 95%) for the task completion time, grouped by the Virtual shadow condition and the Task.

3.5.2 User Experience Questionnaires. The different questions of the subjective questionnaires have been classed into several categories: Shadow Appreciation (SA), Task Appreciation (TA), Agency

(A), Ownership (O) and Presence (P). Table 1 gathers all the questions for the different categories. In the following, the statistical analysis of each questionnaire category is presented:

Shadow Appreciation. In general participants considered that the shadow helped them to perform the task (SA_1: $M = 5$; $IQR = 2$, SA_2: $M = 5$; $IQR = 2$) and also that it was a good indicator of the proximity of the ball with respect to the targets (SA_3: $M = 5$; $IQR = 2$, SA_4: $M = 5.5$; $IQR = 2$) (Figure 9). Wilcoxon signed rank test showed that the male shadow was perceived to provide significantly better assistance when performing the table task (SA_3, $p < 0.05$). A similar trend was observed for the wall task, but results were not significant (SA_4, $p = 0.09$)

Agency. In overall, participants felt that the virtual shadow moved (A_1: $M = 6$; $IQR = 2$), reacted (A_2: $M = 6$; $IQR = 2$) and that they could control it (A_3: $M = 6$; $IQR = 1$) as if it was their own shadow (Figure 9). Wilcoxon signed rank tests did not show any significant differences between the male and female shadows.

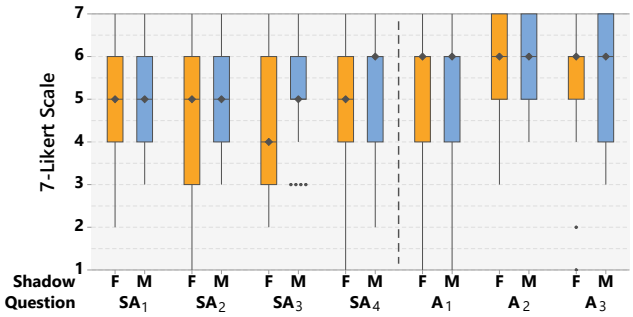

Figure 9: Boxplot summarizing ratings for the shadow appreciation (SA) and agency (A) questionnaires. In general, participants appreciated the fact of having a shadow and felt a strong sense of agency.

Task Appreciation. Friedman rank sum test was used to analyze how participants perceived their accuracy while performing the task (TA_1) and the perceived difficulty (TA_2) considering each level of Shadow (Figure 10). The Friedman analysis of TA_1 showed that the virtual shadow condition had a significant effect [$\chi^2(2) = 10.89$; $p > 0.01$]. Pairwise Wilcoxon tests showed that the condition without shadows was perceived as less accurate (both $p < 0.05$). Similarly, the analysis of TA_2 also showed a significant effect on Shadow [$\chi^2(2) = 12.11$; $p > 0.01$]. Again, pairwise Wilcoxon tests showed that the condition without shadows was perceived to be more difficult (both $p < 0.05$).

Presence. In general, participants experienced a moderate sense of presence. Although participants seemed to rate lower some of the questions for the condition without shadow (see Figure 10), the analysis of the presence questionnaire results did not show any significant on the Virtual shadow condition.

Ownership. In the results related to the feeling of ownership (O_1 and O_2), we observed an interaction effect due to the gender of the participant. In order to analyze the results we considered whether

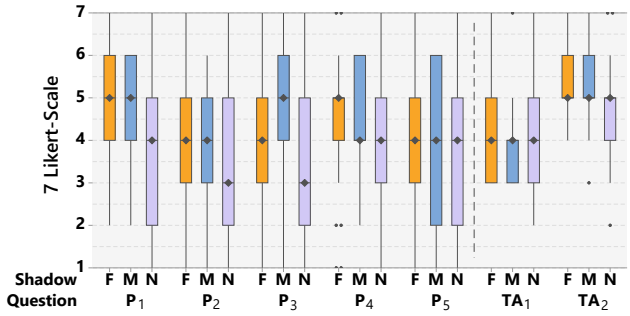

Figure 10: Boxplot summarizing the ratings for the presence (P) and task appreciation (TA) questionnaires.

the shadow was consistent with the gender of the participant or not (see Figure 11). A Wilcoxon signed rank test showed that participants had a higher feeling of ownership (O_1) when the shadow gender was consistent with theirs ($p < 0.05$). The control question (O_2) showed the same result ($p < 0.05$).

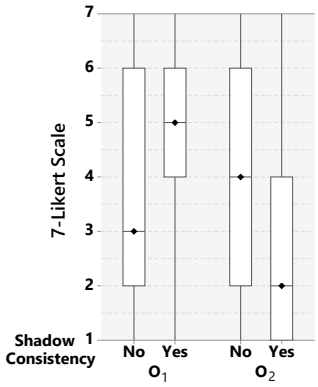

Figure 11: Boxplot of the ownership ratings regarding the shadow consistency in terms of the gender. Ownership ratings were significantly higher when the shadow gender was consistent with the participant's gender.

4 DISCUSSION

Taken together the results should help answering **Q1** and **Q2** to give a lead on, respectively, if virtual shadows can provide a sense of virtual embodiment in IPS and if the virtual shadows increase the spatial perception of the users. In the following we discuss the influence of the virtual shadow on both issues.

4.1 Virtual Shadows and Virtual Embodiment

One of the major research questions in this paper was: Is it possible to embody someone else in an IPS? The questions from categories A and O are taken into account to discuss the virtual embodiment of the users in presence of the virtual shadows. In terms of agency, subjective ratings showed that participants had a strong feeling of agency towards their virtual shadow. Participants had the feeling

that the virtual shadow was moving in a natural way and that it correspond to their shadow position. Some users did not even noticed the shadow at first since it is natural for them to have one:"*I did not payed attention to the shadow: it was natural I guess.*". This effect was not dependent on the morphology of the shadow. Nevertheless, in an IPS users are always aware of their own body and this limitation is reflected on what kind of body the users are able to appropriate. Indeed the ownership measurements depict that when the morphology of the virtual shadow (or the gender) is not consistent with the user's morphology the user tends to feel that the shadow is from someone else. However, as long as the virtual shadow morphology is close enough to the users' one they feel that the virtual shadow is their own. During the experiment some users reacted to the fact that the shadow was of the opposite gender or that the shadow did not had the same hair style for example: "*Is the bun hair style made on purpose ?*", "*Oh. I'm a male now.*", "*I clearly have a female outline*", "*I've got muscles !*", "*Do I wear a bun ?*". Finally, the results in the literature have shown that virtual shadows can increase the sense of presence. Our results show that there is a trend to rate lower the presence question in absence of the shadow which is consistent with the previous work. Some users even commented the enhanced realism of the scene in presence of the virtual shadow: "*The room is not realistic because of the absence of the shadows.*", "*I felt like the experiment was less realistic without the shadow.*", "*I felt it is more realistic with shadows than no shadow at all.*". To sum up, adding dynamic virtual shadows in IPS, such as CAVE displays, can enable the user to embody a virtual shadow. Nevertheless, in order to achieve a higher degree of ownership, the virtual shadow should be close enough to the users body since they are always aware of it.

4.2 Virtual Shadows and Spatial Perception

On the other hand, does the presence of a virtual shadow increase the spatial perception of the users? The performance results, the *SA* and *TA* assessments are taken into account to answer it. If we consider *SA* ratings, participants felt that the virtual shadow could be a good indicator of proximity from the targets and that the shadow was a good assistant to position the ball: "*I mainly used the shadow to position the ball over the targets.*", "*The shadow has been useful even if it was not mine.*", "*The task is more complicated without the presence of a shadow, the distances were harder to estimate.*". The participants had an overall feeling of better perceiving and understanding the virtual environment physical limitations. Moreover, although performance measurements did not show any significant results in terms of task completion time, participants found it easier to perform the task with the presence of a virtual shadow. Some of them even commented it in the questionnaires: "*The shadow was helpful for the ball placements.*", "*It is helpful to have the shadow to place the ball, particularly on the wall.*". Finally, the analysis of the depth error showed that participants had a more conservative behavior when placing the ball on the targets in the presence of virtual shadow. Indeed, the presence of the virtual shadow can warn the users that they are approaching a rigid object and that they may not be able to go through it, as if the object was physically there. An interesting result was the fact that the participants were less accurate when the target was placed in the wall. The most plausible explanation is that it is harder to estimate the actual position of the target when it is placed on the wall, but the actual reasons remain unknown. In summary, these results show that the presence of virtual shadows provides an increased awareness of the spatial relations between the users and the virtual environment (less inter-penetrations) and are positively perceived by the users.

4.3 Limitations and Future Work

In this paper we considered arbitrary human 3D models to generate the virtual shadow of the users. Nevertheless some users may have not been morphologically identified to either the female or the male shadow. It might then be of interest to test our approach with the scanned 3D model of the users in the virtual environment. In the other side the 3D models used were not excessively different from what a human can expect from a shadow. Thus the morphology of the shadow was generally not disturbing. A user study with a remarkably different shadow (see Figure 12) could lead to different results in terms of ownership.

As previously mentioned the lighting of the virtual environment was chosen to provide a noticeable virtual shadow whatever the user's position. Nevertheless we did not carried out any study to evaluate the influence of the lighting conditions on the virtual shadow perception. Such study could help create an even more natural and realistic virtual shadow configuration.

Some participants pointed out that their real shadow, cast on the display floor, was visible when no virtual shadow was present and that it could be awkward and disturbing. A user study should be carried out to validate the hypothesis that the presence of a virtual shadow could overcome the problems and limitations brought by the user's real shadow in front-projected IPS.

For the positioning task we chose to add a real ball in the participants right hand as an extension of their arm. Thus when the virtual shadow of the participant was removed (condition N), the shadow of the ball was also removed. Therefore we did not propose a condition with only the virtual shadow of the ball. According to the previous work the presence of the shadow of the objects adds a depth cue and a study with the shadow of the ball only should lead to results that correspond to the previous studies.

5 CONCLUSION

Compared to HMD, in immersive projection systems the presence of the user's body makes it more difficult to embody a virtual character. We proposed to try and provide the users with a virtual body by adding a dynamic virtual shadow of the user in the environment. We carried out a user study to evaluate the influence of user's dynamic virtual shadows on virtual embodiment and 3D interaction. The experiment showed that, the users had a better spatial perception since they were less prone to go through objects with the virtual shadow. Moreover they appropriate the virtual shadow whenever its morphology was close enough to the user one. The user also felt more comfortable when using the application and they generally felt that the experience was more realistic with their virtual shadows.

In a nutshell, the results of the experiment promote the use of dynamic virtual shadows in IPS and lead the way for further studies on "virtual shadow ownership".

Figure 12: Virtual embodiment through virtual shadows in a VR entertaining application — The virtual shadow of a cowboy (Inspired from the famous *Lucky Luke* comic book) is displayed in a far west virtual scene in our CAVE display.

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