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In-Hand Haptic Representation of User's Surroundings in Virtual Reality

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***Abstract*—The user's awareness of obstacles is essential for safe navigation in Virtual Reality (VR). In this paper, we propose to augment this user's spatial awareness using in-hand haptic feedback. Our approach consists of a multi-actuator haptic handle which acts as a physical representation of the users' surroundings in virtual environments, displaying directional haptic patterns to provide information in function of the user's motions and environment. We conducted a set of user studies to assess the perception of haptic patterns displayed by the handle, and users' ability to avoid dynamic obstacles in VR when the haptic handle is mounted on a joystick. We also evaluated the effect of the device on the perception of the user's personal space in VR. Results show that the proposed technique enables users to effectively avoid moving obstacles by modifying their trajectories. The in-hand haptic representation of the avatar was easily understood by participants, which is promising for future interaction techniques.**

***Index Terms*—Haptics, Virtual Reality**

I. Introduction

We use our personal space [1] in social interactions, but also to process events and to detect the presence of obstacles when navigating [2]. Perception of intrusions in this space, such as ones of obstacles or other users' avatars, is thus essential for comfortable and safe navigation. In virtual environments, the presence of objects or moving entities can be undetected outside of the field of vision or center of attention, raising a series of questions about how to convey this information to the user [3], [4].

One way of providing such information would be to use other sensory modalities such as haptic feedback. In Virtual and Mixed Reality, haptic feedback has gained significant traction, enhancing the realism of users' interactions with virtual content [5]–[7] or providing additional information such as alerts or guidance [8], [9]. This rising popularity is due to its ability to provide rich information distributed throughout the body, to convey diverse pieces of information through the same sensory channel (i.e., the skin), and to avoid overloading the audiovisual sensory channels [10], [11].

Existing approaches for haptic spatial awareness mainly rely on wearable devices such as vests or belts [12]–[15]. In this paper, we propose to explore the use of a handheld multi-actuator device to augment the user's spatial awareness in virtual reality, using the handle as an in-hand representation of their surroundings. While users navigate through virtual environments, feedback is provided about the proximity of obstacles within their surroundings. We conducted a set of user studies, first evaluating users' ability to identify directional cues displayed by the handle. We then assessed the ability of the approach to help users avoid dynamic obstacles and evaluated the influence of this haptic representation of the personal space when walking around static obstacles and virtual humans.

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II. Related work

Personal space is defined as the region around humans in which intrusions from others are perceived as uncomfortable. This space can be modeled in different ways [16], the simplest approach being a series of concentric circles around the user, while more complex representations include a larger area in front of the user or take user's dominant side into account. This space plays an important role in navigating cluttered environments [2], and can change depending on the scenario. In VR, for instance, it was shown that distance from obstacles was higher than in real life [3]. In addition, people also did not show the same behavior with anthropomorphic obstacles than with inanimate objects [17].

Haptics have the potential to add another degree of perception of user's personal space. For example, floor based vibrations rendering the steps of virtual humans were shown to improve social presence in VR, as well as increasing avoidance behavior when virtual humans intruded users personal space [18]. Another study with floor vibrations in augmented reality also highlighted slower walking speeds with haptic feedback than without [19]. Multi-modal cues can also be used to provide warnings when passersby enter the tracking space of the user [4], [20].

In the real world, augmented white canes [21] that use haptic cues to extend the range of detection can be considered as an extension of the user personal space. In VR, Chen et al. [22] used two handles with pin arrays to provide directional feedback around users, displaying projectiles direction or more abstract environmental feedback. However, to the best of our knowledge, no studies have explored how to map the user's personal space to a single handheld haptic interface. The use of sensory feedback to inform users of moving threats was particularly studied by Bajpai et al. in a task where participants had to avoid moving obstacles with the help of combinations of visual, audio, and haptic cues provided by a haptic belt [12]. Tactile cues provided improved users' performance, as did visual feedback which was however considered as more intrusive on the user's field of view. Hence, haptic sensations are often chosen as to avoid overloading the other sensory channels. Similarly, haptic vests have been used to provide cues about the presence of obstacles around the user in a virtual environment [13] or for guidance and alerts [14]. It was proven useful in situations where users could not fully rely on vision, e.g. in a dark or foggy environment. A similar conclusion was drawn in [15], where wearable haptic feedback was used to provide the sensation of bumping into other people when walking in a crowd.

Vibrotactile feedback is a popular modality for handheld navigation information [23]. Some devices rely on a single actuator and specific vibration patterns to communicate information [24], while others use multiple actuators to provide richer or more intuitive information, e.g., representing spatial information using the location of each stimulus [25], [26]. The use of multiple vibration actuators is frequent for wearable interfaces, such as haptic vests [13], armbands [27], or belts [12], but its usage in handheld devices is less common [28].

In this paper, we propose the use of a vibrotactile haptic handle as a representation of the user's surroundings in order to increase user perception of their virtual environment, where previous approaches rather used wearable haptic devices or audio feedback. The design of this multi-actuator device was proposed by Cabaret et al., who also evaluated its use for pedestrian navigation in a real environment [29], [30]. In this work, we take advantage of this design to facilitate the differentiation and recognition of spatial information around the user, enriching their spatial awareness in virtual environments.

III. Design

We chose to use a multi-actuator haptic handle [29] as seen in Figure 1. This device is a 3D-printed, cylindrical handle with four ERM motors on its sides, able to display localized vibrations within the user's hand. Inside, a deformable structure significantly reduces vibration propagation. Motors are connected to an ESP32 board, which controls the vibrations using 3V PWM signals. The VR environment, interactions, and associated feedback are controlled and displayed by a computer running Unity. The movement of the user's avatar in the virtual environment can be controlled using the handle mounted on a joystick (as in Figure 2), or held in hand while walking in VR using a tracker.

The haptic handle communicates the presence of obstacles in the user's personal space. The four vibrotactile actuators around the handle allow for localized haptic feedback in four main directions around the user (Front, Back, Left and Right). By using multiple actuators simultaneously or sequentially, we propose to display four additional directions. We designed two types of tactile patterns to communicate directional information to the user, aiming to render information regarding one's personal space towards 8 different directions (see Figure 1 for an illustration of the patterns):

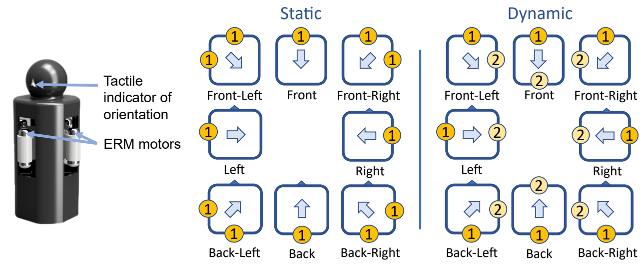

Fig. 1: (left) The multi-actuator haptic handle used in our experiments. (right) `Static` and `Dynamic` feedback cues used to provide directional information about one's personal space. The handle is shown from the top, with the tactile indicator forward; the arrows show the target direction; yellow circles show which motor(s) are activated. or two motors simultaneously. `Dynamic` cues activate two motors, one after another ("1" and then, "2").

- `Static` feedback cues: a single 0.2-s vibration burst is displayed on one actuator (for Left/Right/Front/Back directions) or two adjacent actuators (for diagonal directions).
- `Dynamic` feedback cues: a sequence of 0.15-s vibration burst is displayed on two actuators (e.g. Left and then Right for a Left-to-Right cue).

Vibration durations were chosen empirically, in accordance with actuators technical specifications and previous studies with the device. In the following section, we evaluate and compare the use of these two types of cues. We hypothesize that dynamic cues could convey a directional information about moving objects more easily as they rely on motion inside the hand.

IV. User study

To validate the proposed concept and evaluate the effectiveness of our haptic patterns, we conducted a three-part user study. The first part evaluated the discrimination of the provided directional cues, while the second one evaluated their use to warn participants of moving obstacles in a virtual environment, which they had to avoid. Finally, the third part evaluated the influence of the haptic representation of the personal space on its perception in a proxemics study. The study was approved by Inria's ethics committee (COERLE, saisine générique 2021-39, instance 332).

The first two parts were performed with participants sitting at a desk in front of a screen, with a keyboard, and the haptic handle mounted on a joystick (see Figure 2). Participants were presented with the handle and its representation of the users' surroundings, and then instructed on how to place their dominant hand on the handle before a familiarization phase with the vibrations. A headset played noise throughout the experiment to hide potential audio cues from the actuators.

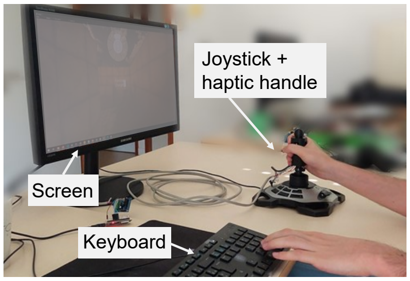

Fig. 2: Experimental setup for studies #1 and #2. Participants sat in front of a screen, holding the haptic handle in their dominant hand. A screen displayed relevant information or the virtual environment. A keyboard was used to answer questions. The handle was mounted on a joystick, keeping it in position for study #1 and used to move the user's avatar in study #2.

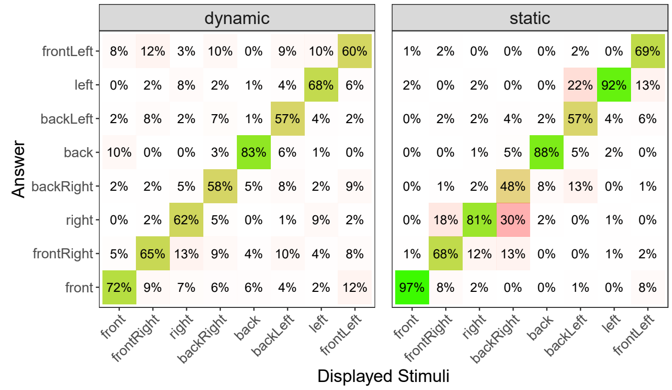

Fig. 3: Experiment #1. Confusion matrix for `Dynamic` (left) and `Static` (right) cues. Participants had to identify the direction communicated by the haptic handle (see Figure 1).

A. User study #1: Discrimination of haptic cues

1) Experimental task and design: First, we evaluated the ability of participants to discriminate the two types of haptic cues provided by the handle (see section III) considering the following conditions:

- *Type of haptic pattern:* `Dynamic` or `Static` feedback.
- *Direction:* eight directions, i.e., `Front`, `Front-left`, `Left`, `Back-left`, `Back`, `Back-right`, `Right` or `Front-right`.

We recruited 12 participants (11 males, 10 right-handed, aged 22–47, mean age 28) to perform in this part of the user study. Four of them reported significant experience with haptic feedback.

The experiment was made of two blocks, one for each type of haptic patterns. The order of the blocks was counter-balanced between participants. During a block, each direction was randomly displayed 10 times, for a total of 80 trials. For each haptic cue, participants had to indicate the direction that was communicated by the handle using a keyboard. The following cue was thens displayed after a short delay. For each trial, we collected the answer of the participants and the time they took to answer after the display of the stimulus. At the end of each block, we asked participants to evaluate the difficulty of the completed task using a 7-point Likert scale. Participants were presented with the different cues before starting.

2) Results: Figure 3 shows the confusion matrix reporting identification rates for both types of haptic pattern. Overall, both types of cues appear to be identifiable, with varying accuracy depending on the type of cues and the direction. Results show `Static` cues to provide better results for the `Front`, `Back`, `Right` and `Left` directions (i.e., the non-diagonal directions) with identification rates ranging from 81 to 97%. Diagonal cues are identified with a lower accuracy, with identification rates ranging from 48 to 69%. On the other hand, identification rates for `Dynamic` cues are generally lower with respect to `Static` ones, with less contrast between directions: identification rates range from 58 to 72%, except the `Back` direction which is identified with 83% accuracy. For `Static` cues, errors tend to be made with adjacent directions, while for `Dynamic` cues, errors spread across all directions.

Individual identification rates show that the lower rates of `Dynamic` cues can be attributed to a few participants who performed worse than the others. Looking at individual results, we can confirm that some participants achieve similar scores in both `Static` and `Dynamic` conditions while some fail in the `Dynamic` condition while succeeding in the `Static` one. Notably, median identification rate is higher for `Dynamic` than for `Static` cues (81% vs. 74%).

We analyzed the identification rates with a Generalised Linear Mixed Model (GLMM), using a logistic model. Independent variables are the type of haptic pattern and the displayed direction. Participants were considered as a random effect. We observed a significant effect of the type of cue (χ^2 (1, N=1920)=34.75, p<0.001), the direction (χ^2 (7, N=1920)=130.39, p<0.001) and a significant interaction between these two variables (χ^2 (7, N=1920)=47.29, p<0.001). Post-hoc tests were performed using Tukey's test. Results show that `Front`, `Left` and `Right` directions are identified with a higher accuracy with `Static` cues than with `Dynamic` cues (p<0.001). In the `Dynamic` condition, the `Back` direction is identified with a higher accuracy than all other directions (p<0.01) with the exception of the `Front` direction. In the `Static` conditions, rear diagonals are identified with lower accuracy than non-diagonal directions (p<0.001).

Regarding the time taken to answer, the median with the `Dynamic` patterns was higher (3.254, IQR=1.218) than the `Static` patterns (1.697, IQR=0.605). This difference was statistically significant according to a Wilcoxon signed-rank test (Z=2.93, p<0.001).

On the subjective difficulty of the task, participants evaluated the `Static` cues as easier to identify (Mean=4.42, SD=1.16) than the `Dynamic` cues (Mean=3.17, SD=1.53). However, only 7 participants out of 12 selected the `Static` cues as their preferred type of cue. Some participants reported that `Dynamic` cues felt easier to identify, but that the mapping to the direction was difficult to understand.

3) Discussion: Results show that both types of cues can be accurately identified by participants, with lower results for the `Dynamic` pattern. These lower results seem to be tied to individuals: most participants showed high accuracy for both types of stimuli, while some showed lower results for `Dynamic` cues. Trials with `Dynamic` cues showed longer answer time, which can be explained by the longer stimulus duration and the difficulty to map the sensation to a direction, reported by participants. Finally, both types of cues show similar performance for diagonal direction, with room for improvements. Given these results, `Static` cues would be the best option for communicating information to the user. `Dynamic` cues could be used, but a longer training phase would be needed before use. A good option would be for users to be able to choose what type of pattern they prefer.

B. User study #2: Moving obstacle avoidance

1) Experimental task and design: In this second experiment, we evaluated the ability of participants to use the directional cues of the haptic handle to avoid moving obstacles approaching toward them. This experiment is inspired by [12], where a haptic belt is used in a similar scenario. Participants were the same as in the previous study. As in the first study, we considered the two types of haptic patterns and eight directions from which the obstacles can approach the user.

The experimental setup and the virtual environment are shown in Figure 2 and 4, respectively. The virtual environment is composed of an octagonal room. At the beginning of each trial, the participant is placed at the center of the room. A moving obstacle is spawned in one of the 8 possible directions and moves towards the center. As the obstacle approaches the user, the latter is alerted by the haptic handle using the haptic patterns discussed previously. Detection occurs 5 m from the user, with obstacles moving at 3 m/s. This experiment was made of two blocks, one for each type of haptic pattern, which were counter-balanced between participants. Each direction was repeated 10 times in each block, for a total of 80 trials completed in a randomized order.

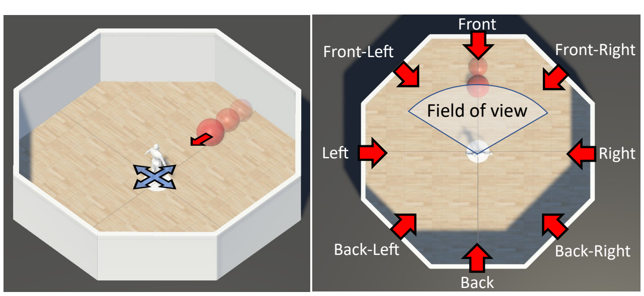

Fig. 4: Virtual environment for study #2. Participants were placed at the center of a virtual room. Obstacles (red spheres) spawned randomly from one of the eight direction that can be displayed by the handle. Participants could see in front of them and had to avoid the obstacles using a joystick.

The haptic handle was mounted on a joystick, enabling the user to move their avatar within the environment to avoid the moving obstacle (the camera orientation is fixed, the virtual avatar can thus only translate, not rotate). Participants were instructed to avoid the moving obstacles relying on the feedback provided by the haptic handle. The point of view of the virtual avatar is shown on the screen in front of participants (see Figure 4), thus enabling them to see obstacles coming from the `Front`, `Front-left` and `Front-right` directions. This is done to replicate the setup used in [12]. At the beginning of each new trial, the avatar was moved back to the center of the virtual room. It was not possible to move before the first feedback cue is provided.

We collected the trajectories of participants in the virtual environment and the number of collisions with obstacles. After each block, participants were asked to rate the task difficulty.

2) Results: Some first observations can be made looking at the success rate, i.e., the number of trials in which the participant avoided the obstacle (see Figure 5). First, we see that when the obstacle is visible (i.e., in the `Front`, `Front-left` and `Front-right` directions), participants are able to avoid it in almost all cases. For the other directions, two cases can be observed: for obstacles coming from the sides (i.e., `Left`, `Right`, `Back-left` and `Back-right` directions), avoidance rates range from 63 to 88%, with slightly higher values in the `Static` condition. For obstacles coming from the `Back`, avoidance rates is much higher at 98%.

Trajectories of the participants can be seen in Figure 6.As we can expect, collisions occur on the path of the obstacle (i.e., for an object coming from `Back-left`, collisions occur on `Back-left` and `Front-right`). We can observe that for obstacles coming from the front-diagonals, participants tend to move either on the side or forward. For obstacles coming from the back-diagonals, participants seem to prefer going toward the other rear-diagonal (e.g., moving toward `Back-left` when an obstacle comes from `Back-right`).

We analyzed the success rates with a Generalised Linear Mixed Model (GLMM), using a logistic model. Independent variables are the type of cue and the direction of the incoming obstacle. Participant are considered as a random effect. Given that the results of the frontal directions, which presented visual

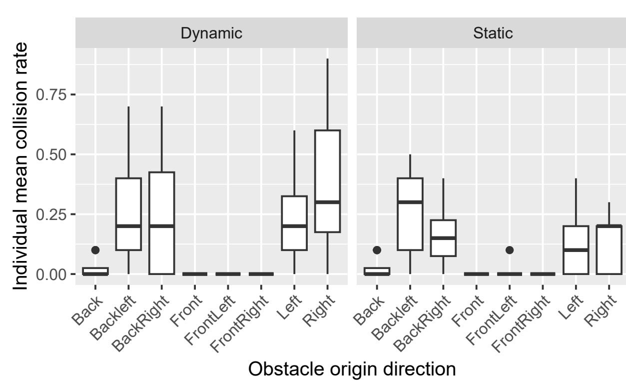

Fig. 5: Distribution of individual collision rates in user study #2 for both types of haptic patterns and each obstacle direction.

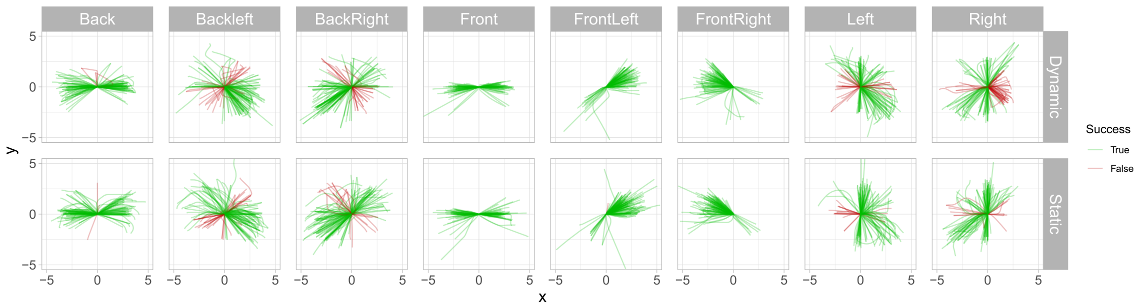

Fig. 6: Participants trajectories in user study #2. Red trajectories indicate trials where a collision occurred.

feedback in addition to haptic feedback, have no variance, we did not include them in this analysis.

We observed a significant effect of both the type of cue (χ^2 (1, N=1200)=18.71, p<0.001) and the obstacle direction (χ^2 (4, N=1200)=43.11, p<0.001). Post-hoc tests were performed using Tukey's test. Results show that avoidance rates are significantly lower in the `Dynamic` condition compared to the `Static` condition (Z=-4.33, p<0.001), and that obstacle coming from the `Back` are avoided better than other those in other directions (p<0.001). Regarding the subjective difficulty of the task, participants rated the ease to avoid obstacles similarly in both conditions (`Static`: Mean=5.25, SD=0.45, `Dynamic`: Mean=5.0, SD=1.20).

3) Discussion: Overall, results show that participants were able to avoid obstacles most of the time. They were however more successful in avoiding obstacles using `Static` cues. One interesting result is the noticeably high avoidance rate for the `Back` direction compared to other non-visible directions. While this could be attributed in part to the higher discrimination rate of this direction, it is still noticeably higher than for `Left` and `Right` directions, which were also well recognized by participants. Bajpai et al. highlighted a similar pattern [12], and argued it might be due to the dynamics of the human body, with a step to the side being faster than a step forward or backward. In our case, movement speed was the same in any direction, but this similarity with real human motion might indicate that users transfer this behavior from the real world.

C. User study #3: Static obstacle avoidance

1) Experimental task and design: In this experiment, we evaluated the effects of a haptic representation of the user's personal space on participants trajectories around static obstacles in VR. Participants walked across a room in VR with one or two obstacles, which were signaled by the haptic handle. Based on the previous studies, we chose to use `Static` cues.

We recruited 12 participants (ages 18-58, 11 M, all right handed) to perform this study. The experiment was conducted in a 8 m×5 m room with a wireless HTC Vive VR headset. The room was recreated at scale in the virtual environment so that participants could walk confidently without worrying about collisions (see Figure 7–right). A tracker was positioned on participants to measure their position, while the handle was linked to a portable battery and controlled wirelessly.

We designed two haptic rendering schemes, each with two levels of vibration depending on the proximity with the closest obstacle. The two levels of proximity correspond to the limits of the personal space (1.2 m) and intimate space (0.45 m) as determined by Hall [1] (see Figure 7–left). The two schemes used series of 0.15 s vibration burst, displayed on one or two actuators (see `Static` in Figure 1). The first scheme, `H_Freq`, used two levels of frequencies (3.3 Hz and 1.6 Hz). The second scheme, `H_Int`, kept a frequency of 3.3 Hz, using two levels of increasing intensity.

For this study, we consider the following conditions:

- *Feedback scheme:* `H_Freq`, `H_Int` or `Visual`.
- *Number of obstacles:* 1 or 2, as seen in Figure 7.
- *Type of obstacles:* human or box obstacle.

The experiment was made of three blocks, one for each feedback condition. The order was counter-balanced across participants. In each block, all combinations of type and number of obstacles were repeated six times in a random order. Across repetitions, we ensured that participants avoided obstacles three times from each side. Obstacles were always visible to participants, even within haptic conditions, and were of the same dimensions. During trials, participants were asked to walk across the room while avoiding the obstacles on their way. A trial ended once they reached the opposite side of the room, starting the following trial after turning around. Before each block, participants were able to familiarize with the active feedback scheme.

We collected participants' trajectories and distances from the virtual obstacles during trials. After each block, participants were asked to judge how careful they were in avoiding both types of obstacles, and how much they relied on haptic and visual feedback.

2) Results: Individual and mean trajectories across conditions are shown in Figure 7. We computed the maximal lateral deviation from each obstacle, mean walking speed and area of the user deviation. We analyzed the effect of experimental conditions on those metrics using separate linear mixed model analysis of variance, followed by post-hoc Tukey's tests.

Results indicated a statistically significant effect on the maximal deviation of the number of obstacles and their type ($p < .001$) but not of the feedback scheme. No significant interactions were observed. Post-hoc tests indicate grater

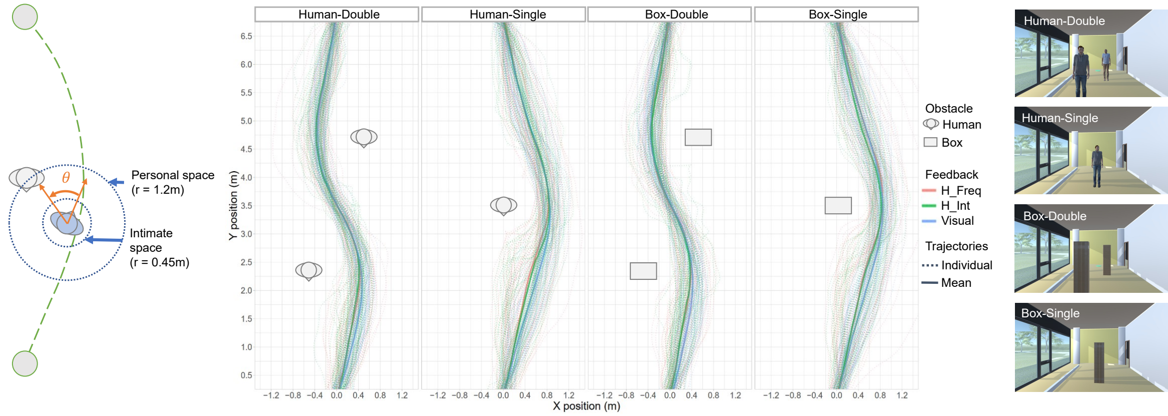

Fig. 7: (left) Users' space is modeled as two circles corresponding to the personal and intimate space. When an obstacle enters this space, the handle is activated in the corresponding direction (i.e., θ is mapped as seen in Figure 1). (middle) Participant walk from one side of the room to the other while avoiding one or two static obstacles (virtual humans or boxes). Individual and mean trajectories are shown across conditions. (right) Screenshots from the point of view of the participants.

deviation in trials with two obstacles ($t(1272)$=7.03, $p < 0.001$), and also in trials with humans ($t(1272)$=4.03, $p < 0.001$).

For trials with a single obstacle, results showed a significant effect on deviation area of the feedback scheme ($p < 0.001$) but not the type of obstacle. Post-hoc tests indicated a smaller area for trials with haptic feedback compared to those with only visual feedback (`H_Freq` vs. `Visual`: $t(415)$=-3.05, $p < 0.01$; `H_Int` vs. `Visual`: $t(415)$=-3.58, $p < 0.01$). For trials with two obstacles, results showed a significant effect on deviation area of both the feedback scheme and the type of obstacle ($p < 0.01$). Post-hoc tests indicated a larger area for trials with human obstacles compared to those with boxes ($t(414)$=3.624, $p < 0.001$), and a smaller area between trials with `H_Int` and `Visual` feedback ($t(414)$=-3.06, $p < 0.01$).

Results indicated a statistically significant effect on mean walking speed of the number of obstacles and feedback scheme ($p < .001$). Post-hoc tests indicated lower mean walking speed in trials with two obstacles than those with one ($t(843)$=-3.64, $p < 0.001$), as well as in trials with haptic feedback compared to visual feedback only (`H_Freq` vs. `Visual`: $t(843)$=-11.08, $p < 0.001$; `H_Int` vs. `Visual`: $t(843)$=-13.55, $p < 0.001$). There was also a significant effect on minimal clearance distance of the feedback scheme ($p < .001$), with slightly lower values in trials with haptic feedback compared to visual feedback only (`H_Freq` vs. `Visual`: $t(843)$=-2.71, $p < 0.05$; `H_Int` vs. `Visual`: $t(843)$=-2.92, $p < 0.01$).

Participants rated their carefulness around both types of objects similarly (`Human`: Mean=5.08, SD=1.59, `Box`: Mean=4.33, SD=1.75). Overall, participants indicated that they relied more on visual feedback than on haptic feedback.

3) Discussion: Results showed that the use of the haptic handle made participants walk somewhat closer to the obstacles. This goes against our initial hypothesis: we expected that the haptic feedback would increase distances from obstacles, as it would have provided an increased sense of intrusion. Participants rated their reliance on the haptic feedback quite low compared to the visual feedback. Similar observations were made in other works [13], [15]. Still, some tended to walk closer to the obstacles at the start of the trials, waiting for the haptic feedback to activate before deviating. Walking speed was also lower with haptic feedback, which could indicate a more careful behavior from participants. As observed in other virtual proxemics studies [17], distance from human obstacles was higher than from inanimate objects. Despite the potential difficulty in mapping the in-hand cues to directions in the environment, the concept of an in-hand haptic representation of the personal space was easily understood by participants, which is promising for future work on the subject. However, increased physical activity compared to the other studies might lower vibration perception and should be investigated further [31].

V. Conclusion

In this paper, we introduced an in-hand haptic representation of the user's surroundings: a haptic handle and associated feedback schemes which represent the user and their personal space. We first evaluated two types of feedback: dynamic and static. Both demonstrated good identification results. Static cues exhibited more consistent results among participants. We then investigated the use of these cues to alert the user of an imminent collision with a moving obstacle in a virtual environment. Both types of cues showed similar results in avoiding the obstacles. Interestingly, participants avoided obstacles approaching from behind them more effectively than those in other directions. Finally, we evaluated the impact of this haptic representation of personal space in a VR proxemics study. The results showed that while participants mostly relied on visual feedback, distance from obstacles and walking speeds were lower when the haptic handle was used.

Future work could envisage using such feedback to inform users of the presence of others in their surroundings, whether they are in the virtual or real world. Another approach could be to display additional sensations, e.g. representing physiological information or interactions with the environment, providing a more complete haptic representation of the users' avatar.

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