Impact of Information Placement and User Representations in VR on Performance and Embodiment

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Abstract—Human sensory processing is sensitive to the proximity of stimuli to the body. It is therefore plausible that these perceptual mechanisms also modulate the detectability of content in VR, depending on its location. We evaluate this in a user study and further explore the impact of the user’s representation during interaction. We also analyze how embodiment and motor performance are influenced by these factors. In a dual-task paradigm, participants executed a motor task, either through virtual hands, virtual controllers, or a keyboard. Simultaneously, they detected visual stimuli appearing in different locations. We found that while actively performing a motor task in the virtual environment, performance in detecting additional visual stimuli is higher when presented near the user’s body. This effect is independent of how the user is represented and only occurs when the user is also engaged in a secondary task. We further found improved motor performance and increased embodiment when interacting through virtual tools and hands in VR, compared to interacting with a keyboard. This study contributes to better understanding the detectability of visual content in VR, depending on its location, as well as the impact of different user representations on information processing, embodiment, and motor performance.

Index Terms—Virtual Reality, Notifications, Peripersonal Space, Embodiment, Multisensory Integration

Figure 1. This study is based on a dual-task paradigm where participants have to quickly identify virtual targets (i.e., a glowing virtual cube) and simultaneously detect visual stimuli appearing in different locations (i.e., a virtual red sphere). Participants performed the task by touching the yellow cube with (A) Hands or (B) Controllers, or by pressing one of four respective keys on a (C) Keyboard. The red sphere that needed to be detected simultaneously can be seen floating in mid-air in each of the images.

1 INTRODUCTION

Designers of Virtual Reality (VR) interfaces need to consider where in a virtual environment information is presented for it to be noticed and processed efficiently. In particular, it may be desired to modulate the saliency of specific content or notifications. Some information is critical and should be noticed immediately, whereas other content should perhaps be placed in locations where it is less distracting. For instance, if users are executing a primary task in VR, they might still want to get notified about new emails, phone calls, calendar reminders, or events occurring in the real-world, without it interfering with the task at hand.

In interaction with desktop computers or touchscreen devices, notifications are often provided visually and can vary in factors such as color, size, movement and duration. In immersive VR notifications are no longer limited to a 2D screen surface, but can be distributed throughout the virtual space. This allows designers to modulate notifications through additional factors, such as the user’s spatial memory, distance perception, peripheral vision, etc. However, until now it is not well understood how the detectability of information in VR is affected by its location in virtual space and its distance with respect to the user.

An important factor to take into account when defining information placement in 3D virtual environments is that of Peripersonal Space (PPS). The PPS has often been conceptualized as the space that is within reach and that we can act upon. It has been found that multisensory information is more efficiently processed within the PPS, than when it is out of reach [1], [2]. Interestingly, active physical and virtual tool use leads to remappings of the PPS, to account for the extended space that is accessible.
through the tool [3]. This process is also known as tool embodiment. Furthermore, recent research suggests that the type of input method used and how the user is virtually represented can impact tool embodiment and PPS configurations in VR [4], [5]. For instance, these studies have shown that tool embodiment is enhanced when having a virtual body representation.

Based on this previous research, the present study aims to contribute to a better understanding of the following three research questions:

- How is information in VR processed, when presented at different distances from the user?
- Does the type of virtual user representation impact the detectability of visual stimuli in VR?
- What role do virtual user representations (i.e., virtual body, tools, or no visual representation) play with respect to the subjective sense of embodiment and mental workload?

The subsequent section describes previous work in more detail, which has inspired and provides theoretical grounds for the present study, focusing on PPS, user representations, and content placement in VR.

2 Related Work

2.1 Peripersonal Space and the Processing of Sensory Information

Mastery in tool-use can be explained in terms of incorporation of tools into the mental representation of our body and the space immediately surrounding it, also known as Peripersonal Space (PPS) [3], [6], [7]. The PPS is defined here as the space that is within reach and that we can act upon. On a neural level, this space is represented through body-centric multimodal populations of neurons, which simultaneously respond to and integrate somatosensory, visual, and auditory information [2]. The space beyond our reach is called the extrapersonal space and is characterized by a different neural coding. Vast amount of evidence has shown that sensory stimuli (i.e., visual, auditory, and tactile) are more efficiently integrated when they are presented within the PPS, compared to when they are presented far away from the body [8], [9]. The boundaries of the PPS have been suggested to be at distances of 40-105 cm from the operating hands, depending on the study [10], [11].

The enhanced multisensory processing within the PPS has been attributed to the role this area plays as a protective buffer zone, preventing harm to the body. When threatening stimuli or warning signals are presented in the PPS, they are treated as a buffer zone, preventing harm to the body. When threatening stimuli occurring near to the user’s body are more efficiently processed, and capture more attentional resources also in VR [11], [14]. However, to our knowledge no study has yet explored how sensory stimuli are detected when located near and far away from the body, while engaging in a dynamic interactive task in VR (e.g., playing a game). Moreover, it has not been evaluated whether awareness of sensory stimuli in different locations is also modulated by how the user is represented in VR. The visual appearance and input methods of a virtual representation have been shown to differently impact users’ perception and tool embodiment, an aspect that we discuss in detail in the following section.

2.2 Virtual Representations of the User in VR

In VR experiences the user is frequently represented through different virtual objects. In the present paper we refer to these virtual objects as user representations and define them as the crucial element of the interface that allows users to carry out actions in the virtual environment [15]. User representations can drastically differ in their visual appearance, the input method, and the mapping of controls. For example, users may be represented through the virtual representation of physical hand-held controllers. These virtual controllers typically look as if they were floating in mid-air (Figure 1B). However, interactions may also be enabled through direct keyboard or controller input, without users seeing any specific representation of themselves in the virtual environment (Figure 1C). An alternative way of representing the user, is through realistic avatars that are experienced from a first-person perspective (Figure 1A). Here body tracking technologies allow direct control of the avatar’s motions based on the user’s own body movements. Such a representation typically leads to the embodiment of the virtual body: users experience that the virtual body is part of their physical body (i.e., body ownership), that they can control it (i.e., agency), and that they are co-located with the virtual body (i.e., self-location) [16], [17], [18].

Evidence has shown that virtual tools, such as cursors or avatars, lead to a remapping of the PPS in order to account for the extended space that is accessible through the virtual object [5], [19], [20]. This process is also known as tool embodiment or extension [7]. A remarkable demonstration of this effect is the impact of using a mouse cursor on the auditory PPS. The use of a mouse cursor seems to link the space near to the user’s body to the virtual space depicted on a computer screen. When users sit in front of a computer not holding a mouse, their response to an auditory stimulus is faster when presented near their right hand than when presented near to the screen. However, this effect disappears after holding or actively using a mouse with the right hand, with enhanced audio-tactile integration occurring when stimuli are presented both near the body and on the screen. Bergstrom-Lehtovirta et al. [5] have expanded on this method and applied it to measure tool extension through visuo-tactile integration in VR. Their results indicate that in VR, tool extension is higher for realistic avatar hands compared to an abstract pointer.
Similarly, Alzayat et al. [4] recently proposed a method to measure tool extension based on attentional processing. Their results suggest that users pay more attention to the task when using direct hand input, compared to controllers.

Studies have demonstrated multiple advantages of interacting through a virtual body in VR. Steed et al. [21] demonstrated that being represented by an active self-avatar results in less mental load when doing a spatial rotation task and subsequently having to recall a sequence of letters. Mohler et al. [22] found that when participants are embodied in an avatar, they are better at judging absolute egocentric distances, compared to not having an avatar. Finally, the results of Maselli et al. [23] indicate that experiencing a body ownership illusion for a virtual body can relax temporal constraints for multisensory integration: Participants are less able to detect latencies between visual and tactile stimuli, than when not being represented by a body.

Despite these varied findings, we are not aware of any research addressing how being represented by an actively controlled self-avatar impacts the processing of visual stimuli with different locations in a 3D space. Moreover, it is not well understood how being represented by a self-avatar, compared to a virtual tool representation or not having a representation, may impact visual information processing in a 3D immersive virtual space. Therefore, the present study aims to address in more detail these phenomena.

### 2.3 Content Placement in VR

The question of where to place virtual content in VR has not yet been widely researched. Some recent studies have investigated the most effective ways of designing and delivering notifications in VR. For example, Ghosh et al. [8] explored the effectiveness of different designs for audio, tactile, and visual notifications in VR and highlight that it is critical to consider their position with respect to the user’s body. Their findings indicate that notifications are effectively detected when co-located with the virtual controllers, however, with the limitation that controllers are often outside the user’s field of view and are used to execute other actions. Moreover, when notifications were presented very close to the user’s body they occasionally caused jump scares. This effect might be related to PPS configurations in order to protect the body from external threats.

Rzariev et al., [24] further investigated this topic, focusing specifically on the placement of notifications in different virtual environments, while users executed various types of tasks. The authors placed notifications either 25 cm in front of the head-set (heads-up display), 15 cm away from the virtual controllers (on-body) on the nearest virtual wall (in-situ), or floating in front of the user at varying distances. Their results indicate that notifications in the heads-up display were more quickly detected, but perceived as more intrusive. In-situ notifications resulted in longer reaction times and more misses. No clear differences in reaction times or hits were observed between the floating and on-body notifications.

Overall, studies researching notifications in VR, highlight the importance of effectively selecting the placement of virtual content with respect to the user’s body. However, we are not aware of any studies that systematically explore the effect of the distance at which notifications are presented with respect to the user’s body. Moreover, notifications consisting of diverse types of content, e.g., ranging from email notifications to a virtual character that talked to the user [24], may introduce confounding variables. Finally, there is no evaluation of how different user representations might impact the detection of notifications [25]. The present study aims to better understand the impact of content placement in VR, controlling for the above-mentioned factors.

### 3 Exploring Information Placement and User Representations

#### 3.1 Experimental Design

We designed a VR experience based on a dual-task paradigm. Users had to quickly execute a motor task (Cube Task), while simultaneously detecting visual information presented in different locations of the 3D space (Sphere Task). Details of the Cube and Sphere Tasks, are given in VR Interaction Tasks section.

The present study was based on a fully counterbalanced within-groups experimental design, where participants completed the dual-task paradigm through either a) a virtual body (i.e., Hands), b) virtual tools (i.e., Controllers) or with c) Keyboard input (no visual representation). The user representation used for each experimental condition can be seen in Figure 1. Additionally, participants underwent a single-task condition that served as a baseline, where before starting with the actual experimental conditions they executed the Sphere Task (i.e., detecting virtual spheres appearing in the 3D environment, without concurrently executing a motor task).

#### 3.2 Hypothesis

Based on the experimental evidence from related work, the present study aimed to test the following hypotheses:

- **H1:** When information is presented near to the user’s body, it is more quickly detected (higher detection performance), compared to when information is presented further away in the virtual space.
- **H2:** Representing the user by means of a virtual body (i.e., hands), will enhance the processing of information presented near to the user’s position, compared to using a virtual tool representation (i.e., virtual controllers floating in mid-air) or to interaction enabled through the use of a physical keyboard.
- **H3:** Representing the user by means of a virtual body leads to better motor performance, enhanced sense of embodiment, and decreased mental workload, compared to the use of a virtual tool (i.e., controllers) or a physical keyboard.

#### 3.3 Study Participants

A total of 24 participants (Mean Age=24.46, Standard Deviation=3.62, 12 Male, 1 left-handed) took part in the study. Inclusion criteria for participants involved not suffering from any type of sensory impairment, no neurological disease, and no intake of psychoactive medications. This study was granted ethical approval by the Ethics Committee of the University of Bayreuth and followed ethical standards according to the Helsinki Declaration. The study lasted approximately one hour and participants received a financial compensation for their participation.

#### 3.4 Interaction Technique and User Representation

The VR scene and experimental setup was implemented using
Unity3D. Users experienced the virtual environment through an HTC Vive Head Mounted Display (HMD).

Different additional equipment and mappings were used, depending on the type of user representation in the following three experimental conditions:

- **Hand:** In this condition, participants saw a pair of virtual hands that were collocated with respect to their real hands. Users’ hand and finger movements were tracked in real time using a Leap Motion sensor that was attached to the front of the HMD. This provided participants with visuo-motor feedback, by linking their real hand movements to those of the virtual hands. During the Cube Task (details below), users interacted with the virtual environment by touching targets with these virtual hands (Figure 1A).

- **Controllers:** Participants saw a pair of virtual controllers floating in mid-air, which were collocated with physical HTC Vive Controllers. The users’ held the physical controllers with their hands. In the Cube Task, users touched virtual targets with these virtual controllers (Figure 1B).

- **Keyboard:** In this condition, no visual representation of the user was provided in the virtual scene. During the experiment users selected virtual targets in the Cube Task by pressing 4 corresponding keys on the keyboard (Figure 1C).

For the Hands and Controllers conditions, touching of targets was triggered using Unity’s built-in collider system. For this purpose, SphereColliders were attached to the virtual hands and the virtual controllers. When one of these colliders intersected with the BoxCollider of the target cube, a touch event was triggered.

### 3.5 Experimental VR Interaction Tasks

This user study was based on a dual-task paradigm, i.e., the user was required to execute two tasks simultaneously. Both tasks, namely the Cube Task and the Sphere Task, are described in detail below.

#### 3.5.1. Cube Task

We designed a motor task based on selecting virtual targets, by touching them with the virtual a) Hands or b) Controllers, or selecting them through c) Keyboard input. In the virtual scene participants saw four targets, which were grey cubes, placed within arm’s reach on a table in front of them (Figure 1). In random order, one of the cubes turned yellow and participants were instructed to select the highlighted cube as quickly as possible. As soon as the yellow cube was selected, its color changed back to grey and another cube in a different location turned yellow instead.

In each experimental condition, the Cube Task was repeated, until all visual stimuli of the simultaneous Sphere Task were presented (see below).

#### 3.5.2. Sphere Task

While executing the Cube Task with each of the different user representations, we requested participants to simultaneously pay attention to visual stimuli and press a pedal with their right foot as soon as they detected the appearance of a red sphere at any location in the scene.

Before the start of the experiment, a baseline for the Sphere Task was recorded: participants were asked to detect the virtual sphere appearing at different location in the 3D space in a single-task paradigm, i.e., without simultaneously executing the Cube Task.

We defined 32 fixed sphere positions distributed in the virtual environment at four different distances from the user: 15cm, 60cm, 285cm, 485cm. At each of these 4 distances, sphere positions were distributed across four horizontal locations and 2 possible heights based on a 3D spherical coordinate system (see Figure 2).

Suitable sphere positions were defined in pilot studies, in which we explored at what angles participants were able to see the sphere, without having to turn their head. Based on the results we decided to place sphere positions at 60, 80, 100 and 120 degrees.

Since we wanted to assess the processing of visual information based on its proximity to the user's body, but not based on varying size or salience of the stimuli, we controlled for the potential influence of such additional factors. We kept the size of the sphere constant in terms of the visual angle, irrespective of its distance to the user, by rescaling the sphere (i.e., the sphere’s size was increased when it was further away and decreased when it was closer). Importantly, we found no indication that participants’ depth perception was hampered by the increased size of far-away objects. Depth perception was provided through binocular disparity and motion parallax from minor head motions during the task, and no difficulties were reported in distinguishing the various distances at which the sphere appeared during the pilot and experimental studies. Further indicators of the sphere’s position were shading and specular highlights.

During the task, only one sphere was displayed at a time, randomly appearing at one of the predefined positions. The sphere was presented for 2500 milliseconds. Participants were requested to press the foot pedal with their right-foot as soon as they detected the red sphere, upon which the sphere would disappear. We recorded the time between the stimulus onset (i.e., red sphere appearing) and the pedal press, and only considered it a hit, if it occurred between 100ms and 2500ms after the sphere appeared. If the sphere remained undetected, i.e., this time elapsed without the participant pressing the pedal, the sphere disappeared automatically. After a short time, the sphere then reappeared at a different location. This inter-stimulus interval ranged from 3000 to 5000 milliseconds and was randomly varied. The specific timings, duration of each stimulus appearance, and inter-stimulus intervals, were established based on the detection response task paradigm [26]. This is a validated paradigm to assess the impact of cognitive load when executing two simultaneous tasks (e.g., driving a car while perceiving different sensory stimuli).

1. [https://unity.com/](https://unity.com/)
3. [https://www.leapmotion.com/](https://www.leapmotion.com/)
Participants were tasked to detect the sphere with highest possible speed and accuracy. The sphere was presented twice in each of the 32 unique locations, in random order. This results in a total of 64 trials.

3.6 Measurements

3.6.1 Detection Performance
To evaluate detection performance for the Sphere Task, we counted the number of times the sphere was correctly detected, and the time taken to respond to each stimulus. First we collected a baseline for detection performance in a single-task condition, during which users could focus exclusively on detecting the sphere. No virtual user representation was given during this task, and the only required input was provided with the foot pedal. These measures were then again recorded in the conditions with dual-task paradigm, when users simultaneously executed the Cube Task with each user representation, respectively.

3.6.2 Motor Performance
We evaluated motor performance through the Cube Task. From this task, we recorded the number of Hits defined by the number of highlighted virtual cubes (i.e., targets) touched during each trial. A hit was only counted if the correct cube was touched. Errors were not counted. One participant was excluded from the detection and motor performance analysis, due to an error in the data collection. Thus, the analysis of these measures was carried out with a total sample size of n=23.

3.6.3 VR Questionnaire
In a questionnaire we included a series of questions addressing different aspects related to the VR experience. These questions were rated on a 7-point Likert scale, with 1 signifying complete disagreement and 7 complete agreement with the statement. The questions are given in Table 1. The body ownership question relates to the perceptual illusion of feeling that the virtual object was part of the real body [27], [28]. The agency and control questionnaire items meant to assess participants’ sense of being responsible for effecting changes in the virtual environment and being able to control their virtual representations. We also included a specific question to measure whether participants felt that their own body was located where they saw their virtual representation, namely self-location. Finally, the questions effectiveness and realism refers to the extent to which participants felt that they could effectively execute the tasks and the degree of immersion they experienced, respectively. All of these questions have been used previously in similar studies [29]. Participants completed a digital version of this questionnaire on a tablet computer, immediately after completing each experimental condition.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Questionnaire Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>body ownership</td>
<td>I had the illusion that the virtual hands / virtual controllers / keyboard were my own hands.</td>
</tr>
<tr>
<td>agency</td>
<td>I felt as if the movements of the virtual hands / virtual controllers / keyboard were caused by my movements.</td>
</tr>
<tr>
<td>control</td>
<td>I felt like I could control the virtual hands / virtual controllers / keyboard as if they were my own hands.</td>
</tr>
<tr>
<td>self-location</td>
<td>I felt as if my hands were located where I saw the virtual hands / virtual controllers / (where I felt the) keyboard</td>
</tr>
<tr>
<td>effectiveness</td>
<td>I felt very effective selecting the cubes with the virtual hands / virtual controllers / keyboard.</td>
</tr>
<tr>
<td>real</td>
<td>The virtual experience felt real.</td>
</tr>
</tbody>
</table>

3.6.4 NASA Task Load Index (TLX)
Once participants finished answering the VR questionnaire, they also completed the NASA TLX [30]. This is a validated questionnaire that evaluates mental workload through 6 sub-scales: mental demand, physical demand, temporal demand, perceived performance, effort, and frustration. These index has been widely used in HCI to measure workload during interaction and in this study we wanted to explore whether subjective workload could vary depending on the type of virtual user representation used.
4 RESULTS

4.1 Detection Performance in Sphere Task

4.1.1 Visual Information Processing Baseline

We first carried out a repeated measures ANOVA on the Detection Times to detect visual stimuli (i.e., virtual red sphere) during the Baseline trial. In this analysis, the factor distance was included with 4 levels, based on visual stimuli appearing very close (15cm), close (60cm), far (285cm), very far (485cm) from the user. On the baseline level, no significant differences were found for Detection Times based on distance (F(3,66)=15.01, p=2.67, partial η2=0.09; Figure 4). In the baseline condition, participants achieved a 100% success rate, detecting the sphere all 64 times, as it appeared twice in each of the 32 predefined locations in the virtual environment.

4.1.2 Visual Information Processing during Cube Task

We also analyzed Detection Times for visual stimuli when participants had to execute two tasks in parallel: focus on touching the glowing cubes (Cube Task) and simultaneously detecting the red sphere (Sphere Task). A repeated measures ANOVA was used to analyze whether visual stimuli were detected differently during the Cube Task, based on distance (15cm, 60cm, 285cm, 485cm) and the user representation (Hands, Controllers, and Keyboard). This analysis shows a significant main effect of distance on the time taken to detect visual stimuli (F(3,66)=20.07, p<0.01, partial η2=0.48). No main effect of user representation (F(3,66)=0.68, p=0.51, partial η2=0.03) or interaction between distance*user representation was found (F(6, 132)=0.23, p=0.96, partial η2=0.01). Further, post-hoc LSD tests showed that the further away the notification appeared, the longer participants took to detect the visual stimulus (Table 2). Reaction times were shorter for visual stimuli appearing on the front row (15 cm) and longer for the last row (485cm), as can be seen in Figure 5. Residual errors of the ANOVA were normally distributed based on Shapiro-Wilk tests. The results of post-hoc tests (Table 2) remain significant after correcting for multiple comparisons using the false discovery rate method [31], except for the difference between 60cm to 285cm which is a trend (p=0.03).

Overall, the number of undetected stimuli was very low. Per distance and across all conditions, the sphere appeared 1104 times, and averaging across all conditions participants only missed 2.08% stimuli at 15 cm distance, 1.81% at 60cm, 5.43% at 285cm, and 5.34% at 485cm. This means that in most trials participants were successful in detecting the sphere every time it appeared.

![Figure 3. Boxplot showing the detection time for visual stimuli by distance from the user during the Baseline trial.](image)

![Figure 4. Boxplot showing the detection time for visual stimuli by distance from the user, with each user representation.](image)

<table>
<thead>
<tr>
<th>Distance (I)</th>
<th>Distance (J)</th>
<th>Mean Difference (I-J)</th>
<th>St.Error</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>15cm</td>
<td>60cm</td>
<td>-.057</td>
<td>.013</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>285cm</td>
<td>60cm</td>
<td>-.099</td>
<td>.014</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>485cm</td>
<td>60cm</td>
<td>-.113</td>
<td>.014</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>60cm</td>
<td>15cm</td>
<td>.057</td>
<td>.013</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>285cm</td>
<td>15cm</td>
<td>-.042</td>
<td>.018</td>
<td>.030</td>
</tr>
<tr>
<td>485cm</td>
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<td>-.056</td>
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<td>.01</td>
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<td>485cm</td>
<td>485cm</td>
<td>.014</td>
<td>.016</td>
<td>.369</td>
</tr>
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</table>
4.2 Motor Performance in the Cube Task

A repeated measures ANOVA showed a main effect of Condition (Hands, Controllers, or Keyboard) on the number of Hits accomplished in the Cube Task (\(F(2,44)=15.01, p<0.01\), partial \(\eta^2=0.41\)). Further post-hoc comparisons, with Bonferroni corrections, showed that participants accomplished a significantly higher number of Hits (i.e., number of virtual cubes touched) with the virtual Hands \(p<0.01\) and Controllers \(p<0.01\) in comparison to the Keyboard. No significant difference in motor performance was found between the Hands and Controllers (see Figure 3). The residual errors of the ANOVA were normally distributed.

Moreover, a repeated measures ANOVA revealed that there were no significant differences in the time taken to complete the tasks \(F(2,44)=1.28, p=0.29\), partial \(\eta^2=0.06\) between the Hands (mean duration=311.34ms, \(sd=10.52\)), Controllers (mean duration=309.23ms, \(sd=12.61\)), and Keyboard (mean duration=307.61ms, \(sd=13.02\)) conditions.

4.3 VR Questionnaire

4.3.1 Body Ownership, Agency, and Self-Location

Friedman tests indicate that there was a significant difference in feelings of body ownership \(\chi^2=30.50, \text{df}=2, p<0.001\) and agency \(\chi^2=11.56, \text{df}=2, p=0.003\) between user representations (i.e., Hands, Controllers, and Keyboard). As shown in Figure 6, further Wilcoxon paired comparisons showed that reported body ownership \(p<0.01\) and agency \(p<0.01\) scores were significantly higher when interacting using virtual Hands compared to a Keyboard. Participants also reported higher body ownership for the virtual Hands compared to the Controllers \(p<0.01\), whereas these conditions did not differ in terms of perceived sense of agency \(p=1.00\). No significant differences in body ownership \(p=0.08\) and agency \(p=0.09\) were found between the Controllers and the Keyboard conditions. Moreover, no significant differences were found between user representations in regards to the sense of self-location (Friedman Test; \(\chi^2=3.65, \text{df}=2, p=0.16\)).

4.3.2 Control, Realism, and Effectiveness

In terms of perceived control there was a clear difference between user representations (Friedman Test; \(\chi^2=20.73, \text{df}=2, p<0.001\)). This difference can be seen also in Figure 7. Wilcoxon tests indicated that the degree of perceived Control was comparable when interacting with Hands and Controllers \(p=0.13\). However, participants reported a higher perception of control when using the Hands \(p<0.01\) and Controllers \(p<0.01\), compared to the Keyboard. Participants also perceived significant differences in terms of realism \(\chi^2=7.49, \text{df}=2, p=0.02\) and effectiveness \(\chi^2=9.74, \text{df}=2, p<0.01\) of the interaction. Wilcoxon signed rank tests indicate that the Hands condition was perceived as more realistic when compared to the Keyboard \(p<0.01\), with no differences between the Hands and the Controllers \(p=0.59\), or between the Controllers and Keyboard \(p=0.13\). For perceived effectiveness we found that ratings were higher when they interacted through the virtual Hands \(p=0.02\) or the Controllers \(p<0.01\), compared to Keyboard inputs. Again, there were no differences in reported effectiveness when comparing the Hands and Controllers \(p=0.55\).
4.4 NASA TLX

According to Shapiro-Wilk tests, the data of the different NASA TLX sub-scales was not normally distributed. For this reason, this data was analyzed using Friedman tests. When a significant difference was found, we further explored the differences between conditions using paired-comparisons with Wilcoxon signed rank tests. Figure 8 summarizes the scores given by participants in the different NASA TLX sub-scales, based on the type of user representation.

We found a significant difference between user representations in Mental Demand (Friedman: $\chi^2=11.93$, df=2, $p<0.01$) and Performance (Friedman: $\chi^2=11.93$, df=2, $p<0.01$). Paired comparisons revealed that Mental Demand was significantly higher in the Keyboard condition, when compared to both the Hands ($p<0.01$) and the Controllers ($p=0.04$) conditions. Whereas, subjective Performance was higher for the Hands ($p=0.04$) and Controllers ($p=0.01$) conditions when compared to the Keyboard. No significant difference between the Hands and Controller in these measures were found.

We did not find any other significant difference in the rest of NASA TLX sub-scales: Physical Demand (Friedman: $\chi^2=3.05$, df=2, $p=0.22$), Temporal Demand ($\chi^2=1.27$, df=2, $p=0.53$), Effort (Friedman: $\chi^2=2.92$, df=2, $p=0.23$), and Frustration (Friedman: $\chi^2=2.63$, df=2, $p=0.27$).

![Figure 8. Boxplot with results from the NASA TLX questionnaire, showing different scores with each user representation.](image)

5 Discussion

The evidence from our study strongly supports our first hypothesis: Detection performance of visual information was significantly influenced by distance, with information presented near the user’s physical body being more quickly detected. However, this effect occurred only in the dual-task paradigm, but not during the baseline control condition where participants did not execute actions with their hands in the virtual environment. This suggests that the location of visual stimuli plays a prominent role in their detectability during active interaction in VR, with no noticeable impact of distance when the user is passive. No support was found for our second hypothesis, since distance modulated the detectability of visual information equally for all user representations (i.e., Controllers, Hands, or interaction enabled by a Keyboard). Finally, our third hypothesis was partially supported: users indeed reported a strong sense of embodiment and lower mental workload when interacting with virtual Hands, but to some extent this was also the case when using Controllers. Interacting through virtual Hands or Controllers also positively impacted motor performance, compared to using a Keyboard.

Our findings support the notion that the PPS plays an important role in linking the user’s body position to stimuli located in the virtual environment. This in accordance with past evidence showing enhanced sensory processing and awareness of information presented in the space immediately surrounding the body, namely the PPS [9, 11, 13, 14]. However, we also found that differences between detecting near and far away virtual objects, were dependent on being actively engaged in a motor task in VR. Importantly, this motor task included clear visual feedback of the actions executed by the user in the virtual environment through a user representation, namely a virtual tool. No differences in detection performance was found in the baseline trial, where the user was passive. This is in line with the study of Avenanti et al. [32], where it was found that the premotor cortex plays a crucial role in mapping sensory representations of space onto the motor system. Moreover, these findings are also in accordance with studies showing that active interaction with the environment, tool manipulation, and the motor system, are critical to establish PPS configurations [25], [33]. The present study expands this knowledge, by suggesting that active interaction also plays an important role in defining the boundaries of PPS also in VR.

The above findings might also be related to the perception of near and far away objects depending on whether the virtual body is visible or invisible [14]. In this regard, it has been found that humans make predictions about objects that might produce a sensation as they come near the visible body (e.g., touch), thus establishing a difference between the near and far space [3]. Noel et al. [14] found that when the body is rendered invisible in VR, there is a higher probability of perceiving visual and proprioceptive events as coupled together in space, somehow hindering perception of the near and far space. Whereas, when participants see a virtual collocated body, this multisensory coupling decreases, evidencing a clear distinction of the space near and far away from the body. Based on this findings, the authors argue that the visible body is an important constituent in constructing the PPS. Our results partly support this evidence, since a clear distinction between the near and far space was indeed absent during the baseline trial, where the user was rendered invisible. However, our results expands on Noel et al. [14] findings, since we found that there is a discrimination of objects’ distances with respect to the body, even when users do not have a body representation but still can observe the immediate results of their motor actions. This was the case when users interacted in the virtual environment using virtual controllers or Keyboard inputs. In both cases, users perceive immediate feedback of their actions in the virtual environment, since the virtual cube immediately changed color in response to being touch with the controllers or selected with a key press. This highlights the importance of being able to act and observe the immediate consequences of our actions in the physical and virtual world, for the establishment of PPS configurations.

The studies of Ghosh et al. [8] and Rzayev et al. [24] show that in VR notifications are more quickly detected, when
presented near to the user's body (i.e., on controllers or in front of the face). At the same time, stimuli in this space were judged as more disruptive. We speculate that such perceived intrusiveness might be related to the PPS’s function as a protective buffer zone for the body [12]. It is therefore recommendable to present virtual content at a more comfortable distance from the users, unless information of great importance must be communicated. It should be noted that, although in our study users took longer to detect visual information that was located further away, the sphere was still correctly detected eventually in the vast majority of cases (i.e., few misses). This suggests that in a simple VR scenario, not including additional visual distractors, placing virtual content in the background may still result in effective, albeit slower, detection. However, this might not be the case in more complex VR scenes that include further distractors and interactions. In this cases, it is possible that the presence of more complex actions and distractors, hinders the detectability of content presented on the background. This is an aspect that should be researched by future studies.

Another possible explanation for the differences in detection performance found between the baseline and the dual-task conditions, may be related to divided attention mechanisms and limited available cognitive resources [34]. It is plausible that having more cognitive resources available during the baseline trial (i.e., not performing a concurrent motor task), resulted in a more efficient processing of stimuli appearing at different distances. Whereas, the limited amount of cognitive resources in the dual-task paradigm, may have led to a prioritization of closer stimuli. However, this perspective does not fully explain the observed linear relationship between detection performance and distance, with reaction times gradually increasing as visual stimuli are presented further away.

Contrary to our expectations, being represented by a virtual self-avatar (i.e., Hands) did not lead to an increased awareness of near visual stimuli, compared to interacting through Controllers or a Keyboard. All three conditions resulted in similar detection patterns, and a prioritization of near stimuli in the dual-task paradigm. This finding appears to stand in contrast to the results reported by Steed et al. [21], according to which a self-avatar leads to less cognitive load, compared to not being represented by an avatar. However, in this study we used different tasks, user representations, and input devices (e.g., controllers or a keyboard), which may account for the different findings.

Importantly, this research tried to control for several factors that may influence the processing of visual information in VR. First, a single type of simple visual stimulus was used (i.e., red sphere). This allowed us to test visual stimuli processing based only on distance and the user representation, without further confounding effects from additional cognitive processing that may be required for complex stimuli (e.g., email notifications or a talking avatar). Second, we systematically controlled for the size of the visual stimulus, to ensure that it was equally salient at all distances. Third, the presentation duration of stimuli was based on the detection response task [26], a well validated measure for assessing mental workload when multitasking. Finally, for the first time, we have researched how visual stimuli are processed at different distances in connection to the virtual representation of the user.

Nevertheless, despite the care taken to control several confounds, there are still factors that could have played a role in the observed results. For example, when experiencing VR through an HMD we are prone to suffer from the Vergence-Accommodation (VA) conflict [35]. The focus distance of virtual objects, which the eyes have to accommodate to, is usually fixed at infinity. In contrast, the eyes’ vergence might be adjusted differently for close objects, such that a conflict between vergence and accommodation arises. This leads to contradicting depth cues. However, it is highly unlikely that the VA conflict explains the present results, since a completely different pattern of results were found between the baseline control (i.e., single-task) condition and the actual experimental trials (i.e., dual-task paradigm). If the VA conflict accounted for the present findings, it is likely that participants would have detected visual stimuli in the 3D space following the same patterns in the baseline condition compared to the actual experimental trials based on the provided depth cues. However, this is not the case, since there are evident differences in detectability between the baseline condition and the actual experimental trials (i.e., dual-task).

Finally, in accordance with past research, we have found that the type of user representation seems to modulate embodiment and motor performance. The present findings indicate that direct manipulation through Hands and Controllers leads to better motor performance in the Cube Task, compared to interaction through Keyboard input. It may be argued that the lower performance with the Keyboard could be due to the user having to learn a more complicated mapping (assigning keys to cube locations) that required further cognitive and motor processing. This is also supported by the increased mental workload found in this condition. If this is the case, the results can be expected to improve with training, which should be further explored in future studies. However, reaching for targets in VR using our hands or handheld tools parallels the actions we would carry out in the physical world, making it well suitable for novice users. Moreover, virtual hand representations have been shown to result in perceptual improvements [36], [37]. Thus, interactions are potentially more intuitive [38], require lower cognitive load [39] and lead to higher presence in VR, when direct manipulation is involved. Finally, in accordance with other studies, we have found that the sense of body ownership is strongest when interacting through a virtual body (i.e., Hands) [40]. To some extent, users also experienced a sense of embodiment over the Controllers, in perceiving high agency and control over the actions executed through them, as well as self-location at the controllers’ position.

6 Future Work

The user study presented in this paper explores information presentation from the perspective of visual processing, depending on stimulus distance and the impact of user representations in VR. There are several further aspects which future research should explore. For example, processing of different modalities (audio/visual), or visual stimuli of higher complexity (e.g., email notifications or animated objects) may vary. Further, it remains to be studied, whether the difference in processing near and far stimuli depends on the primary task being a motor task, or whether it merely requires a local focus of limited attention (e.g., when watching an engaging movie on a virtual handheld screen). The question then follows, what happens when this focus of attention or task space is indeed further away? Are stimuli prioritized when they are near the focus of attention, instead of within the observed results. For example, when experiencing VR through an HMD we are prone to suffer from the Vergence-Accommodation (VA) conflict [35]. The focus distance of virtual objects, which the eyes have to accommodate to, is usually fixed at infinity. In contrast, the eyes’ vergence might be adjusted differently for close objects, such that a conflict between vergence and accommodation arises. This leads to contradicting depth cues. However, it is highly unlikely that the VA conflict explains the present results, since a completely different pattern of results were found between the baseline control (i.e., single-task) condition and the actual experimental trials (i.e., dual-task paradigm). If the VA conflict accounted for the present findings, it is likely that participants would have detected visual stimuli in the 3D space following the same patterns in the baseline condition compared to the actual experimental trials based on the provided depth cues. However, this is not the case, since there are evident differences in detectability between the baseline condition and the actual experimental trials (i.e., dual-task).

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the PPS? It may also be argued that we develop a certain PPS over time, as we learn to interact with our environment through our hands and tools. Such a “habitual PPS” may then persist even in VR, if the virtual scene features familiar structures of plausible size (e.g., furniture). In absence of a visual user representation, this may then be established based on the objects in our environment and may lead to a PPS untypically large or small extent.

Future work on information presentation in VR should also carefully explore the use of other characteristics already applied for designing notifications in 2D (movement, size, color, duration), as well as VR-specific characteristics (semantics of specific locations in a room). Furthermore, in VR the user’s attention may perhaps be captured through subtle ambient changes, e.g., in lighting or soundscape.

Finally, it remains to be better understood what reasons underlie the differences observed between the baseline and the experimental trials. We believe that this can be linked to the fact that in one condition participants were not interacting in VR (baseline), while in the other conditions they were actively executing actions. The differences may then be explained in terms of how a visible user representation might influence visuo-proproceptive coupling. Another plausible explanation could be that the dual-task paradigm was more cognitively demanding than the baseline and therefore required prioritization of certain stimuli. Future research should explore this further to try and disentangle these potential factors.

7 Conclusion

In this paper we explore information processing in a dual-task paradigm within an immersive virtual environment. We find that, while engaged in a motor task, performance in detecting visual stimuli is higher if these are presented near the user’s body. However, such different processing of near and far stimuli does not occur when the user is passive (i.e., solely focusing on detecting the stimuli). Furthermore, we observed no difference in information processing when varying the type of user representation: contrary to our expectations, interacting through a virtual body does not appear to affect sensory processing of visual stimuli, compared to interacting through controllers or no visual representation (Keyboard). The user representation did however impact motor performance and embodiment, which are increased when having body or tool representation.

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