Notification in VR: The Effect of Notification Placement, Task, and Environment

Rufat Rzayev[1,2], **Sven Mayer**[2,3], **Christian Krauter**[2], **Niels Henze**[1,2]
[1] University of Regensburg, Regensburg, Germany, firstname.lastname@ur.de
[2] University of Stuttgart, Stuttgart, Germany, firstname.lastname@vis.uni-stuttgart.de
[3] Human-Computer Interaction Institute, Carnegie Mellon University, PA, US, info@sven-mayer.com

ABSTRACT

Virtual reality (VR) is commonly used for entertainment applications but is also increasingly employed for a large number of use cases such as digital prototyping or training workers. Here, VR is key to present an immersive secondary world. VR enables experiences that are close to reality, regardless of time and place. However, highly immersive VR can result in missing digital information from the real world, such as important notifications. For efficient notification presentation in VR, it is necessary to understand how notifications should be integrated in VR without breaking the immersion. Thus, we conducted a study with 24 participants to investigate notification placement in VR while playing games, learning, and solving problems. We compared placing notifications using a *Head-Up Display*, *On-Body*, *Floating*, and *In-Situ* in open, semi-open, and closed VR environments. We found significant effects of notification placement and task on how notifications are perceived in VR. Insights from our study inform the design of VR applications that support digital notifications.

CCS Concepts

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

Author Keywords

Notifications; Virtual Reality; Interruption; Presence.

INTRODUCTION

VR is increasingly used for a large number of applications, including learning, digital prototyping, therapy, training, education, and most importantly, entertainment [15, 17]. It combines visual, auditory, and in some cases haptic feedback to create the feeling of presence in immersive simulations. The feeling of presence is conveyed by a virtual environment that occupies our senses, captures our attention, and fosters our active involvement [50]. Modern VR technologies provide users with strong feelings of "being there" while disconnecting them from the real world [24]. However, complete sensorial isolation from the real world is not always desirable, as it can cause missing important notification, create social isolation, and even harm the user.

Current interactive systems, especially mobile devices, provide time-sensitive information through digital notifications. These notifications can announce important messages, upcoming calendar events, and calls. Previous work showed that mobile notifications are viewed within minutes [26, 33]. However, disconnection from the real world as the result of the immersion in VR can result in missing important notifications, *e.g.*, calls or events. Being disconnected from notifications can even cause anxiousness and loneliness [28]. Moreover, requiring users to remove the VR headset to view and respond to notifications will destroy the immersion.

Today's VR systems, such as the HTC Vive or Google Daydream, already display notifications in VR. Here, notifications are shown as an overlay pop-up in front of the user. The unexpected pop-up might interrupt the experience, presence, and ultimately, the immersion. Thus, the presentation can negatively affect the VR experience. Recently, Ghosh *et al.* [12] investigated how to present interruptions in VR which are caused by the real world, such as a person in the room, or a nearby wall. They used visual, audio, and haptic components to notify the user. While Ghosh *et al.* cover a wide range of possible methods to notify users, digital notifications are distinctly different as they have no immediate impact on the user. Consequently, it is not clear how notifications should be presented in VR and how this is affected by the user's task and the VR environment.

In this paper, we investigate the effect of notification placement on the VR experience while systematically manipulating the VR tasks and virtual environments. In a study with 24 participants, we compared four notification placements: *Head-Up Display*, *On-Body*, *Floating*, and *In-Situ*. Participants were immersed in one of three environments while performing three different tasks during which they had to respond to notifications. To cover a wider range of possible tasks in VR, we used three different tasks: *Gaming*, *Learning* and *Problem solving*. Inspired by current VR games and applications [23, 42, 43], we designed three environments: an open-air village (*Open*), a spaceship (*Semi-Open*), and a room-scaled museum exhibition (*Closed*). By comparing the notification placements and tasks in virtual environments, we provide the following

CHI PLAY '19 October 22–25, 2019, Barcelona, Spain

ISBN 978-1-4503-6688-5/19/10. . . 15.00

DOI: https://doi.org/10.1145/3311350.3347190

contributions: (1) Through quantitative and qualitative results, we show that notification placement and the user's task significantly affect how notifications are perceived in VR; (2) We provide three design implications for future VR applications that support notification presentation.

RELATED WORK

Our work is based on previous research investigating bringing real-world information into VR, digital notifications, and information placement in VR that we discuss in the following.

Missing Real World Information

Current VR headsets occupy the user's view on the real world. This can lead to missing important real-world information, such as physical objects around the user and digital information from outside the VR. It can be advantageous to completely shield users from the real world for some VR use cases. VR can, for example, reduce pain by diverting the user's attention away from the symptoms associated with the real-world painful medical intervention [13, 35]. However, for other VR use cases, such as entertainment, it can be essential to inform users about the real world.

Previous work investigated how to inform VR users about the surrounding physical environment. In Substitutional Reality, every physical object surrounding the user was paired with a virtual counterpart [40]. Likewise, several works investigated using depth maps to generate dynamically immersive and interactive VR environments using the surrounding real-world objects as templates [38, 41]. Moreover, several methods were proposed supporting the interaction between VR users and the surrounding physical world [5, 18].

Digital Notifications

Notification is a visual, auditory, or haptic alert designed to attract the attention of users by proactively delivering information [16, 29]. Various systems were suggested that investigate notification delivery in a multi-device environment [7, 21, 46], on public and smart displays [45, 49], on-body [20, 34] and in a smart home environment [44]. Daily, a large number of notifications is delivered to mobile device users [26]. In addition to benefits from delivering valuable information, ill-timed notifications can lead to distractions [26]. However, disabling notifications leads to the anxiousness of missing important information and violating the expectation of others [27, 28].

Digital Notifications in VR

There are several commercial and research solutions available to view digital notifications in VR. The users of the HTC Vive can check their incoming notifications using a companion Android or IOS application on their smartphone. Wearing the VR headset, users can be informed about incoming calls, text messages and calendar events. Short information about notifications is displayed in front of the user on a blue background. To read the complete notifications and to respond to them, users need to open HTC Vive's notifications panel. Samsung's Gear VR and Google's Daydream also inform about received notifications using pop-ups. However, to get more details about the notifications, users need to pause the VR experience and visit their VR dashboards. Zephyr [10] is an open-source project that enables mirroring all kinds of Android notifications to OpenVR compatible VR headsets. These VR solutions have in common that they display notifications either as a pop-up in a predefined distance from the user or in a VR dashboard. In the case of a pop-up view, these solutions have the same presentation for all notifications and do not take the current VR context into account. Consequently, they can cause frustration and adversely affect the perceived VR presence. On the other hand, VR dashboards provide the possibility to reply to notifications at the cost of interrupting the VR experience. George *et al.* [11] investigated the effect of interruption caused by text, ambient and spotlight notifications on the feeling of presence in VR. They found that virtual text affects the level of presence more negatively, compared to ambient and spotlight notifications. However, the reaction to text notifications is significantly faster than the other two notification types.

Zenner *et al.* [52] implemented an open-source framework that facilitates receiving notifications from a companion Android application while being immersed in VR. With an example application, they demonstrated the usage of the framework to display immersive and context adapted notifications in VR. In the application, notifications were shown on a public display inside a supermarket. Based on the current task in VR and the priority of notifications provided by the Android app, three levels of animations were shown to notify the user: no animation, spotlight animation that drew attention to the display, and cage animation that inhibited the user from continuing with the current task. However, no study was conducted to compare these notification methods.

Previous work also investigated Augmented Virtuality (AV) to enable viewing digital notifications in VR. Desai *et al.* [8] presented a method that enables augmenting VR with the view of a smartphone's screen. To ascertain the intention of the user to view the smartphone, the proposed method utilized a Leap Motion attached to the VR headset. As the presence of the smartphone in front of the users was detected, they could view a stream of screenshots from their smartphone in VR. In comparison, Alaee *et al.* [1] attached an RGBD camera to a VR headset to facilitate the user to interact with the smartphone. However, using these methods, a user needs to interact with the real-world object that does not belong to the VR system, and the view is not adaptable in VR.

Ghosh *et al.* [12] investigated notifications in VR by comparing visual, audio, and haptic modalities and their pair-wise combinations without considering various VR tasks and environments. In a study, participants had to react to notifications while teleporting in an environment and performing a task. As a result of the study, several design recommendations for VR notifications using various feedback modalities were proposed. First, real-world notifications in VR must be distinguishable by design. Second, controllers can be used as effective locations for VR notifications. Third, the placement and design of notifications should reduce visual search, avoid jump scares, and use familiar metaphors. Finally, users should be able to interact with and easily dismiss notifications.

Text Placement in Head-Mounted Displays

Digital notifications are mainly based on textual information. Several related works investigated various aspects of text placement in a head-mounted display (HMD). Orlosky *et al.* [25] found that users prefer to place text on the background rather than on the screen of an HMD. Furthermore, they presented a system that automatically moved text displayed through an HMD to a more visible place on the background. Chua *et al.* [6] investigated nine physical display positions of a monocular HMD to show notifications in dual-task scenarios. They found that the notifications displayed in the middle and bottom center positions are the most noticeable. The further results revealed that the top and the peripheral positions are more comfortable, unobtrusive, and preferred. Rzayev *et al.* [32] found that text displayed on the top-right position of smart-glasses increases subjective workload and reduces comprehension compared to the center and the bottom-center positions. Rothe *et al.* [31] compared static (*i.e.*, the text is in a fixed position to the viewer and statically connected to the HMD) and dynamic (*i.e.*, the text is near the speaker) subtitles in 360° videos. In the study, they found that dynamic subtitles might lead to a higher score of presence, less sickness, and lower workload. Sidenmark *et al.* [39] presented three techniques that use eye tracking to present subtitles in interactive VR.

Summary

In summary, previous research explored the integration of notifications in VR, placement of external information in HMD as well as the use of different modalities. However, insights on the environment and task-independent presentation of interactable notifications in VR are missing.

STUDY

We conducted a study that investigates how to present digital notifications in VR. We compared four notification PLACEMENTs while performing three TASKs in three virtual ENVIRONMENTs. Thus, we employed a mixed design with three independent variables: PLACEMENT, TASK, and ENVIRONMENT. For the different PLACEMENTs, we showed notifications on a *Head-Up Display*, attached to the user's controller (*On-Body*), as a *Floating* display, and in the surrounding virtual environment (*In-Situ*), see Figure 1. The placement and the design of notification were in line with the design recommendations by Ghosh *et al.* [12]. For the TASKs, we selected *Gaming*, *Learning*, and *ProblemSolving* tasks, which are common VR use-cases [15], see Figure 3. As ENVIRONMENTs, we used three virtual worlds with different sceneries and containing different objects: an open-air village (*Open*), a spaceship bride (*Semi-Open*), and a museum exhibition (*Closed*), see Figure 2. The open-air village represented an outdoor virtual environment which has been frequently used in 360° videos and games [42]. The spaceship bride was a prototype for a semi-open virtual environment that has been mainly used in science fiction games [43]. Virtual exhibitions are frequently used for the education of cultural heritage [36]. Our museum exhibition was a room-scaled closed environment that resembled experiences frequently found in indie games, such as Job Simulator [22].

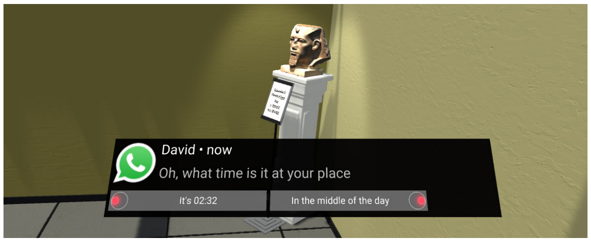
We used ENVIRONMENT as a between-subjects variable as this enabled us to run the study in less than one hour, which counteracts possible fatigue effects. Thus, a group of eight participants experienced each ENVIRONMENT. The order of PLACEMENT was counterbalanced across all participants, and the order of TASK was randomized within PLACEMENT. As an apparatus, we used a Windows 10 PC with an NVIDIA GeForce GTX 1080, Intel i7, and 32GB RAM connected to the HTC Vive. The software was implemented in Unity using open-source assets.

Measurements

During the study, if a notification was not answered within 15 seconds, it was removed and counted as a missed notification. The number of missed notifications (*Missed Notification Count*) was measured as a dependent variable. As further dependent variables, we measured the amount of time it takes to respond to a notification (*Response Time*) and the absolute change of the distances of a participant to the current notification at the times the notification was displayed and answered (*Answering Distance*). To measure the effect of notifications in VR, we used the questions about noticeability, understandability, perceived urgency and perceived hindrance of notifications (*Notifications in VR*) taken from Ghosh *et al.* [12]. Furthermore, we measured the usability with the System Usability Scale (SUS) questionnaire [4] and the presence using the Igroup Presence Questionnaire (IPQ) [37] and the Presence Questionnaire (PQ) [50]. Moreover, we adapted the five questions about notification mechanisms (*Notifications Mechanisms*) by Weber *et al.* [45]. We used PQ to analyze if all ENVIRONMENTs result in the same sense of presence. Finally, we asked participants to provide qualitative feedback in a semi-structured interview.

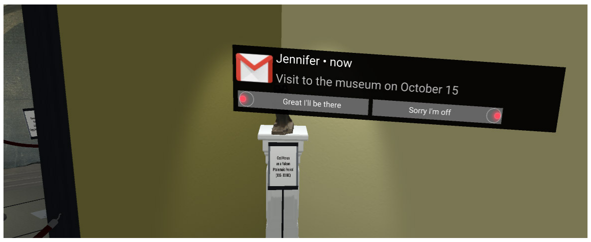
Notification Design

For the study, we used realistic notifications. To not violate the participants' privacy by collecting their personal data, one researcher collected his own notifications using the Notification Log app [48]. 60 notifications were selected from nine different apps and categorized into messaging, group messaging, email, social, non-social categories approximating the mean distribution of notifications received per user per day [29]. To personalize notifications, we replaced names and times with placeholders. During the study, for each participant, we replaced the name placeholders with real names and time placeholders with the current time. Furthermore, to provide interaction with notifications, we added two possible natural responses to each notification. The responses were created by three researchers and resembled responses provided by a system like Google's Smart Reply [19]. We designed notifications by considering the state-of-the-art notification design and design recommendations for notifications [12, 45]. They had a rectangular shape, were showing notification text, app icon, triggering time and two buttons below for the responses, see Figure 1. For better readability, we used a dark background color with light sans-serif text, which is in line with the guidelines for using text in VR [9]. To interact with notifications, participants could use the round trackpad of the HTC Vive controllers without the need to look at a notification

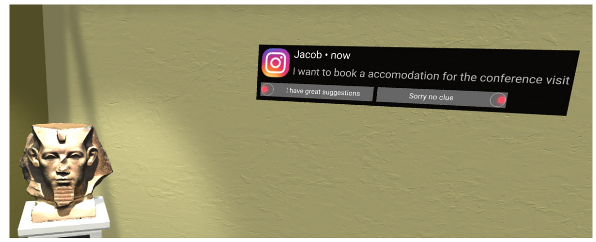


(a) *Head-Up Display* - Notification attached to the headset

(b) *On-Body* - Notification attached to the controller



(c) *Floating* - Notification as a floating display



(d) *In-Situ* - Notification at the wall

Figure 1. Four notification PLACEMENTs used for the study.

or aim on it. Pressing on the left or right side of the trackpad triggered the corresponding response button; hence, the button was highlighted with the red color to indicate the selection, and the notification was dismissed. To ensure that participants would not accidentally press on the trackpads, they were only used to respond to an active notification.

Notification Placements

While the *Head-Up Display* and *On-Body* conditions placed notifications directly on the participant, in the *Floating* and *In-Situ* conditions, they were attached to the close-by location.

Head-Up Display placement resembled the interface design of traditional video games. Here, notifications were displayed 0.25 meter away from the front of the VR headset and were 25° pitched, see Figure 1a. Since a text displayed in the bottom-center position results in higher comprehension than the others while walking [32], the notifications were shown in the center of the lower half of the field-of-view.

The *On-Body* condition was inspired by smartwatches; notifications were attached to the controller of the participant's dominant hand, see Figure 1b. For this placement, we positioned notifications on the outer side of the controller in a distance of 15 cm and pitched by 60°. The selected rotation and distance made it easier to read a notification over the participant's wrist as the extension of it and reduced the need to raise the controller in front of the eyes.

For *In-Situ*, notifications were placed on a wall, see Figure 1d. We used a raycasting method to determine the wall to place a notification. For this placement, we neglected the pitch of the head not to display notifications at the floor, on the ceiling or in the sky. If the ray intersected with a wall, we used this point to display a notification. In all other cases (*i.e.*, intersection with a window or an open door), we used the nearest wall to the intersection and then found the nearest point between this wall and the participant. After a position on a wall was found, we tested if the notification was colliding with any other object. If so, the notification was moved towards the center of the room until the area was free. If not, we displayed the notification on this wall.

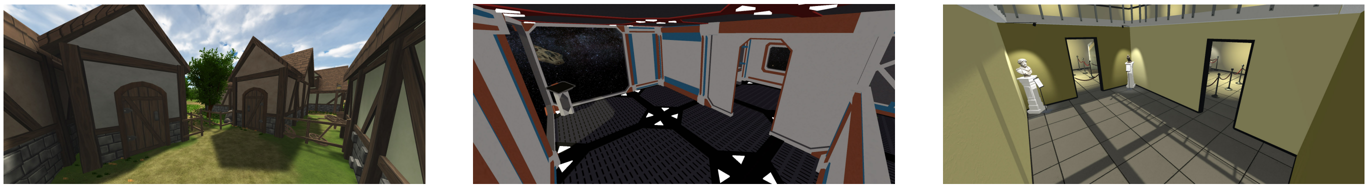
For *Floating*, notifications were positioned freely floating in front of the user in the height of 1.5 meters, see Figure 1c. We used the same method as in the *In-Situ* to find the wall in front of the participant. However, in this placement, the location of a notification depended on the distance between the participant and the wall. To avoid jump scares by displaying notifications too close to the participants, and to make notifications appear neither on the walls nor outside of the virtual room, we applied following rules: (1) If there was more than two meters distance between the participant and the wall, we placed the notification one meter in front of the participant. (2) If the distance was two meters or less, the notification was placed one meter away from the wall.

Tasks

For the evaluation, we implemented three primary tasks which participants had to perform while being in the environments: *Gaming*, *Learning*, and *ProblemSolving*, see Figure 3. The tasks were designed to involve common VR interactions, including visual search, navigation, exploration, pointing and clicking.

For the *Gaming* task, we implemented a simple ball collection task where participants walked within the environment and collected all randomly in free-space appearing balls with a controller. Upon touching a ball with a controller, it was removed, and a new ball appeared.

For the *Learning* task, participants had to solve text comprehension tests by reading texts and afterward answering a question. The task involved basic learning activities, such as focusing on the content and solving a problem. We used text paragraphs with an average length of 515 characters ($SD = 109$)



(a) *Open* - An outdoor farmer village (b) *Semi-Open* - A spaceship bride (c) *Closed* - A museum exhibition

Figure 2. Three virtual environments used for the study.

(a) *Gaming* - A ball collection game (b) *Learning* - A comprehension test (c) *ProblemSolving* - A card sorting task

Figure 3. Three tasks participants had to perform during the user study.

and questions from a collection adapted from the book *Speed Reading: A Course for Learners of English* [30]. The texts were displayed altering on two boards positioned at opposite ends of the virtual environment. After reading the text, participants could press the virtual button (see Figure 3b) to view the question. Four possible answers were shown on the board. After answering the question, the right answer was displayed on the board, and the participants had to walk to the other board for the next text.

For the *ProblemSolving* task, we implemented a VR version of the card sorting task by Berg [2]. The cards were alternatingly displayed on the tables positioned at the opposite ends of the virtual environment, similarly as in the *Learning* task, see Figure 3c. Participants could sort the cards by using the laser pointer attached to the virtual controller. For the task, we used a deck of 64 cards having one of three features with four possibilities. The features were the form (triangle, star, plus, circle), the color (red, green, yellow, blue) and the count (1,2,3,4). Participants had to sort the cards onto four target cards (one red triangle, two green stars, three yellow plus symbols, and four blue circles). To sort a card, participants had to point the corresponding button below the target card and click the trigger button on the controller. The cards had to be sorted by one of the three features, whereas the rule was randomly chosen and unknown to the participant. After five cards were correctly sorted, the rule was changed. After each sorting move, the feedback was provided above the target cards to inform whether a card was correctly sorted. After ten cards were sorted (including the wrong moves), the task transferred to the next table. Thus, participants had to walk to the next table to continue to sort the cards. If all cards were sorted, they were automatically shuffled to continue.

Virtual Environments

The tracking volume in our lab was approximately 4×5 meters, and participants could freely walk within this obstacle-free area. For our three ENVIRONMENTs, we used full tracking space. Each of the ENVIRONMENTs had a virtual door or a grate located where participants could enter and leave the ENVIRONMENT to start and end the study but also to fill questionnaires between the conditions. Each ENVIRONMENT is shown in Figure 2. They had the same walkable area with the door or a grate at the same place. The *Open* environment represented by a small open-air farmer village, the *Semi-Open* environment was a spaceship bride with a view into the outer space, and the *Closed* environment was an exhibition in a museum.

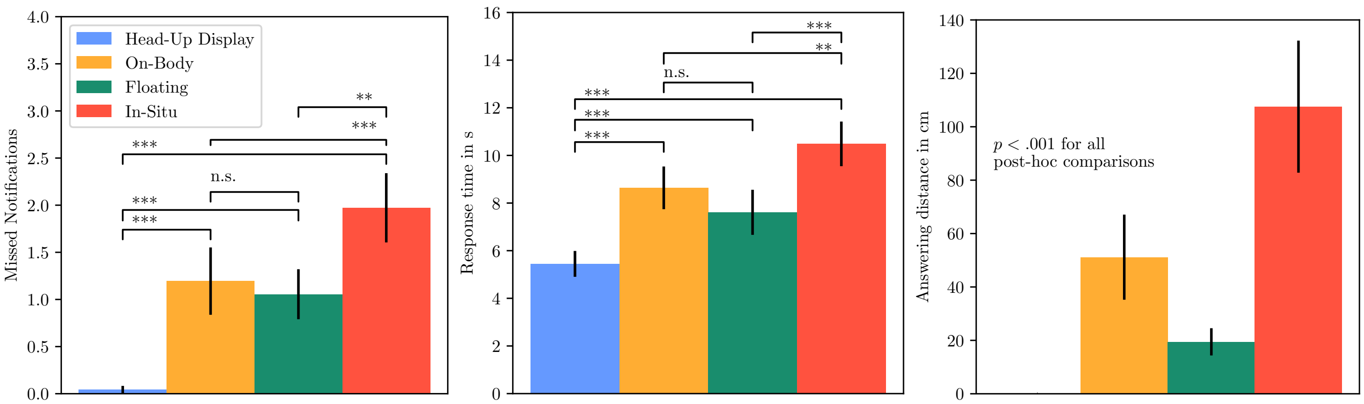
Participants

We recruited 24 participants (6 female, and 18 male) through our university's mailing list. The age ranged from 17 to 26 years ($M = 25.0$, $SD = 4.3$). All of them had either normal or corrected-to-normal vision. While only 2 participants never used a VR device, 12 used it more than once, and 10 used a VR device more than three times. We compensated participation with € 10.

Procedure

After welcoming the participants, we explained the procedure of the study. We then asked them to sign an informed consent form and answer demographic questions. Besides, we asked participants for 15 names of persons from whom they frequently receive mobile notifications to fill our name placeholders of notifications. We explained to participants how to interact with notifications and that notifications which were not responded within 15 seconds would be automatically dismissed. Then we helped participants to put on the VR headset and ensured that they were standing at the virtual door, the start and end point of each condition. To familiarize participants with all tasks and notification representation, we used an empty virtual tutorial room. Here participants could try the tasks, and interact with notifications.

After leaving the tutorial room through the virtual door, participants experienced all PLACEMENTs $\times$ TASKs pairs in one ENVIRONMENT. They performed all tasks one by one with one PLACEMENT. Each TASK continued for three minutes.



(a) Missed Notification Count (b) Response Time (c) Answering Distance

Figure 4. Diagrams displaying collected objective data. With * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$ and all others are not significant (n.s.).

	Missed Notification Count					Response Time					Answering Distance				
	df_{effect}	df_{error}	F	p	Partial η^2	df_{effect}	df_{error}	F	p	Partial η^2	df_{effect}	df_{error}	F	p	Partial η^2
E	2	21	.891	.425	0.078	2	21	1.083	.356	0.093	2	21	0.244	.785	0.023
T	2	42	99.764	.000	0.826	1.967	41.318	88.487	.001	0.808	2	42	0.812	.45	0.037
P	3	63	51.472	.000	0.71	1.821	38.258	38.553	.001	0.647	1.335	28.035	53.06	.001	0.716
E × T	4	42	3.112	.025	0.228	4	42	0.916	.463	0.08	4	42	0.155	.959	0.014
E × P	6	63	1.651	.148	0.135	3.643	38.258	1.049	.402	0.09	1.335	28.035	0.1	.946	0.009
T × P	6	126	27.441	.000	0.566	3.964	83.244	22.292	.001	0.514	2.442	51.282	3.757	.023	0.152
E × T × P	12	126	1.825	.051	0.148	10.571	2183.244	0.812	.636	0.071	4.884	51.282	0.183	.965	0.017

Table 1. ANOVA main effects and interactions for *Missed Notification Count*, *Responce Time* and *Answering Distance*. (With E - ENVIRONMENT, T - TASK, P - PLACEMENT)

During a task, participants received five notifications in random intervals between 20 and 40 seconds. If a participant did not answer a notification within 15 seconds, it was removed and considered as missed. After finishing all TASKs with one PLACEMENT, a message was displayed informing participants to leave the room through the door. Then we helped participants to take off the headset and asked them to fill the questionnaires. In addition, we asked participants to give feedback regarding the PLACEMENT, TASK and ENVIRONMENT. Participants filled the questionnaires after performing all TASKs with one PLACEMENT to not to interrupt the VR experience frequently. Afterward, participants continued with the remaining PLACEMENT conditions. These steps were repeated until the participant was subject to all four PLACEMENTs. In the end, we asked participants to complete the PQ questionnaire and conducted a semi-structured interview. The study took about an hour and 15 minutes.

RESULTS

During the study, 24 participants completed three tasks for each of the four PLACEMENTs and received five notifications during each task. For the evaluation, we performed a quantitative analysis of the collected objective and subjective data. For the nonparametric data, we applied the Aligned Rank Transform (ART) using the ARTool toolkit [1] and applied paired-sample t-test with Tukey correction, as suggested by Wobbrock *et al.* [51]. For all other analysis of variance (ANOVA)s, we used paired-sample t-test with Bonferroni correction. Whenever Mauchly's test showed that the sphericity assumption was violated in the ANOVA, we report Greenhouse-Geisser (GG) or Huynh-Feldt (HF) corrected p-values.

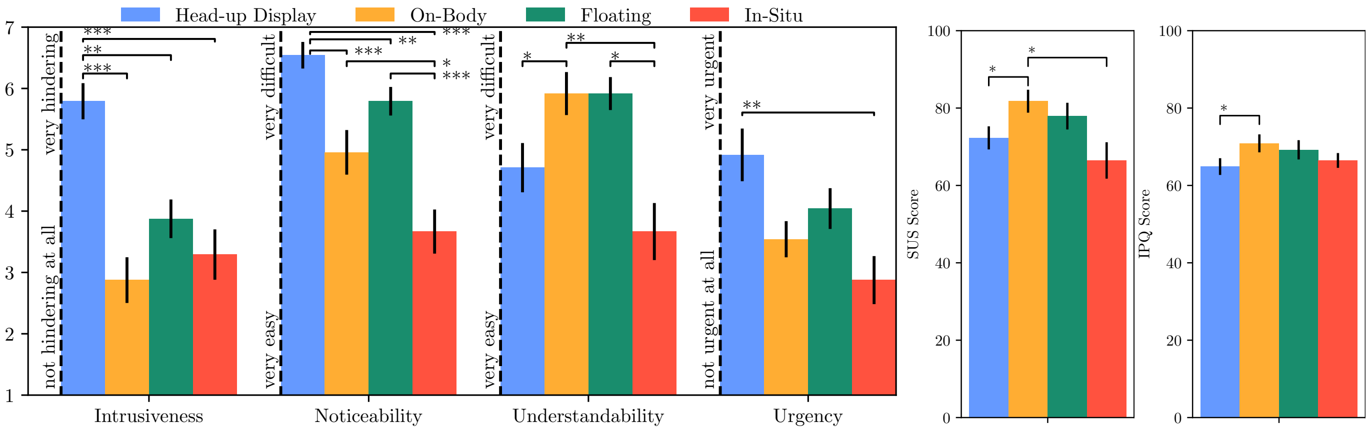
[1] http://depts.washington.edu/ilab/proj/art

Objective Results

To reveal the main effect of PLACEMENT, TASK, and ENVIRONMENT on *Missed Notification Count*, *Response Time* and *Answering Distance*, we applied three-way mixed ANOVAs. The results are summarized in Table 1.

Missed Notification Count. There were statistically significant main effects of TASK and PLACEMENT and two-way interaction effects of PLACEMENT × TASK and TASK × ENVIRONMENT. Post hoc tests revealed that all comparisons of TASKs were statistically significant ($p < .001$) ($M = 0.3$, $SD = 0.9$; $M = 1.8$, $SD = 1.7$; $M = 1.1$, $SD = 1.7$; respectively for *Gaming*, *Learning*, and *ProblemSolving*). For PLACEMENT, all pairwise comparisons except *Floating* vs. *On-Body* ($p > .063$) were statistically significant ($p < .01$), see Figure 4a. The *Learning* task led to significantly higher missed notification count than *Gaming* and *ProblemSolving* while using *Floating* (all $p < .001$) and *On-Body* (all $p < .005$) placements. Compared to other tasks, *Gaming* resulted in the least missed notification count while displaying notifications using *In-Situ* placement (all $p < .001$).

Response Time. The *Response Time* of missed notifications was 15 seconds, as this was the maximum time a notification was shown. There was a statistically significant main effect of PLACEMENT and TASK and two-way interaction effect of TASK × PLACEMENT. The pairwise comparison of TASKs



(a) Notifications in VR Questionnaire (b) SUS (c) IPQ

Figure 5. Average scales of the *Notification in VR* questionnaire, *SUS*, and *IPQ* scores. With * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$ and all others are not significant (n.s.).

	Intrusiveness					Noticeability					Understandability				
	df_{effect}	df_{error}	F	p	Partial η^2	df_{effect}	df_{error}	F	p	Partial η^2	df_{effect}	df_{error}	F	p	Partial η^2
E	2	20	0.072	.93	0.007	2	20	0.388	.683	0.037	2	20	0.088	.915	0.009
P	3	63	13.05	.000	0.383	3	63	19.261	.000	0.478	3	63	10.918	.000	0.342
E × P	6	63	1.783	.116	0.145	6	63	0.987	.441	0.086	6	63	1.877	.098	0.151
	Urgency					SUS					IPQ				
	df_{effect}	df_{error}	F	p	Partial η^2	df_{effect}	df_{error}	F	p	Partial η^2	df_{effect}	df_{error}	F	p	Partial η^2
E	2	20	2.313	.124	0.187	2	21	0.126	.882	0.012	2	21	1.009	.381	0.087
P	3	63	5.215	.002	0.198	2.154	45.234	4.371	.007	0.172	3	63	3.365	.024	0.138
E × P	6	63	0.363	.899	0.033	4.308	25.234	0.746	.615	0.066	6	63	0.343	.911	0.032

Table 2. ANOVA main effects and interactions for *Notification in VR Questionnaire*, *SUS* and *IPQ*. (With E - ENVIRONMENT, T - TASK, P - PLACEMENT)

revealed that all comparisons were statistically significant with $p < .001$ ($M = 6.5$s, $SD = 2.2$; $M = 9.7$s, $SD = 3.6$; $M = 7.9$s, $SD = 3.8$; respectively for *Gaming*, *Learning*, and *Problem-Solving*). For PLACEMENT, post hoc tests showed statistically significant difference ($p < .002$) between all except *Floating* and *On-Body* ($p > .063$), see Figure 4b. *Learning* task led to significantly higher response time than *Gaming* and *Problem-Solving* while using *Floating* (all $p < .001$) and *On-Body* (all $p < .005$) placements. Compared to other tasks, *Gaming* resulted in the least response time while displaying notifications using the *In-Situ* placement (all $p < .001$).

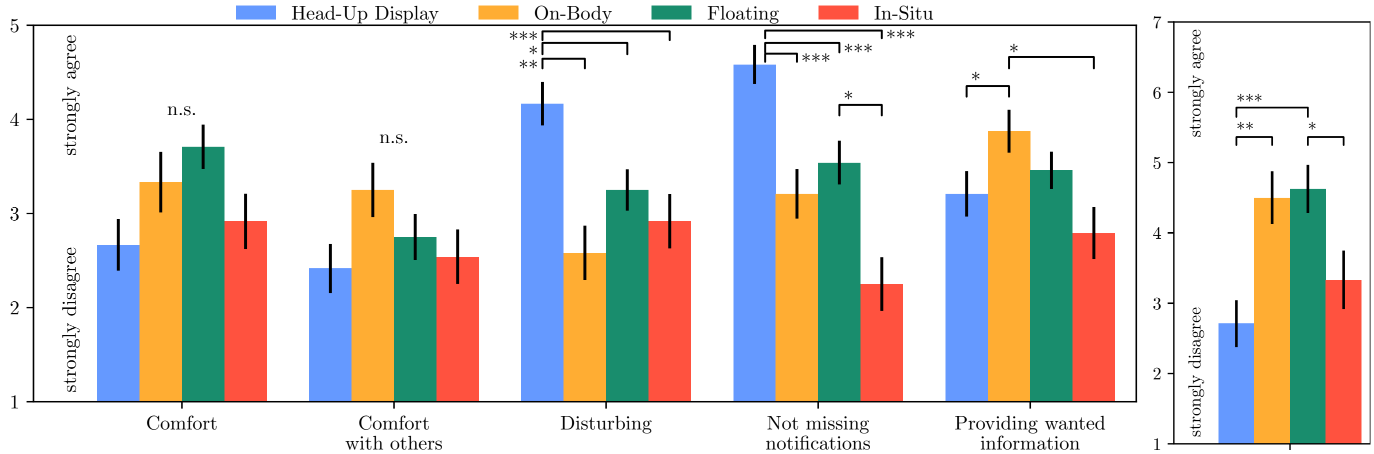
Answering Distance. For the *Head-Up Display* placement, the distance to notifications was always the same. We found a statistically significant main effect of PLACEMENT and two-way interaction effect of PLACEMENT × TASK. Pairwise comparisons for PLACEMENT showed that all comparisons were statistically significant ($p < .001$), see Figure 4c. Compared to other tasks, *Gaming* resulted in the highest answering distance while displaying notifications using *On-Body* placement (all $p < .001$).

Subjective Results

Following, we report the analyses of the subjective data that we collected through questionnaires that participants filled out after experiencing each placement with all tasks. As these results are task-independent, we conducted two-way ANOVAs to find the main effect of ENVIRONMENT and PLACEMENT on the *IPQ* and *SUS* scores, as well as on the scales of questionnaires about the *Notifications in VR* taken from Ghosh *et al.* [12] and the *Notification Mechanism* adapted from Weber *et al.* [45]. The results are summarized in Table 2 and Table 3.

To compare the main effect of the ENVIRONMENT on the sense of presence, we applied a one-way ANOVA on the data collected at the end of the study using the questionnaire by Witmer *et al.* [50]. There was no statistically significant main effect of ENVIRONMENT ($F_{2,21} = 2.467$, $p > .109$). We argue that the presence feeling in all ENVIRONMENTs was the same with an average score of $M = 167$ ($SD = 9$), out of a maximum score of 224. It indicates that the VR experience in all ENVIRONMENTs provided a considerable level of feeling of presence.

Notifications in VR Questionnaire. Following, we present the results of the questionnaire that comes with four scales: *Intrusiveness*, *Noticeability*, *Understandability*, and *Urgency* (see Figure 5a). There was a statistically significant main effect of PLACEMENT for all scales. However, for all scales, we did not find any further statistically significant main or interaction effects. For *Intrusiveness*, post hoc t-tests revealed statistically significant differences between *Floating* and *Head-Up Display* ($p < .003$), *On-Body* and *Head-Up Display* ($p < .001$), and *Head-Up Display* and *In-Situ* ($p < .001$). For *Noticeability*, pairwise comparison showed statistically significant differences with $p < .05$ between all except *Floating* and *On-Body*



(a) Questionnaire about Notification Mechanism

(b) Participant's preference

Figure 6. Average scales of the *Notification Mechanism* questionnaire and question about participant's preference. With * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$ and all others are not significant (n.s.).

	Comfort					Comfort with others					Disturbing				
	df_{effect}	df_{error}	F	p	Partial η^2	df_{effect}	df_{error}	F	p	Partial η^2	df_{effect}	df_{error}	F	p	Partial η^2
E	2	21	0.133	.875	0.012	2	21	1.603	.225	0.132	2	21	0.704	.505	0.062
P	3	63	2.313	.084	0.099	3	63	2.101	.109	0.09	3	63	8.049	.000	0.277
E × P	6	63	0.178	.981	0.016	6	63	1.924	.09	0.155	6	63	2.776	.018	0.209

	Not missing information					Providing wanted information					Participant's preference				
	df_{effect}	df_{error}	F	p	Partial η^2	df_{effect}	df_{error}	F	p	Partial η^2	df_{effect}	df_{error}	F	p	Partial η^2
E	2	21	1.502	.245	0.125	2	21	0.153	.859	0.014	2	21	0.69	.512	0.062
P	3	63	19.076	.000	0.475	3	63	6.424	.000	0.234	3	63	8.16	.000	0.279
E × P	6	63	1.625	.154	0.134	6	63	0.241	.961	0.022	6	63	0.743	.617	0.066

Table 3. ANOVA main effects and interactions for the scales of *Questionnaire about Notification Mechanism* and participant's preference. (With E - ENVIRONMENT, T - TASK, P - PLACEMENT)

($p = .57$) placements. For *Understandability*, post hoc test revealed statistically significant differences between *Floating* and *In-Situ* ($p < .001$), *On-Body* and *Head-Up Display* ($p < .029$), and *On-Body* and *In-Situ* ($p < .001$). For *Urgency*, post hoc test revealed that only the difference between *Head-Up Display* and *In-Situ* was statistically significant ($p < .001$).

System Usability Scale Questionnaire. There was a statistically significant main effect of PLACEMENT on *SUS* score. No other statistically significant main or interaction effects were found. Post hoc test revealed significant differences in *SUS* scores between *In-Situ* and *On-Body* ($p = .033$), and *Head-Up Display* and *On-Body* ($p = .021$) placements, see Figure 5b.

Igroup Presence Questionnaire. We found a statistically significant main effect of PLACEMENT on *IPQ* score. There was no statistically significant main effect of ENVIRONMENT which was in line with the results of the *Presence Questionnaire*. No statistically significant interaction effect was found. Post hoc test showed a significant difference in *IPQ* scores between *Head-Up Display* and *On-Body* ($p < .023$) placements, see Figure 5c.

Questionnaire about Notification Mechanism. We analyzed the data that we collected using the questionnaire about the notification mechanism that was adapted from Weber *et al.* [45], see Figure 6a. The questionnaire had the following five statements with 5-item Likert scales each: (1) I would feel comfortable using this notification mechanism when I am in VR alone (*Comfort*); (2) I would feel comfortable using this notification mechanism when I am in VR with others (*Comfort with others*); (3) This notification mechanism disturbs my VR experience (*Disturbing*); (4) With this notification mechanism, I have the feeling that I am not missing a notification anymore (*Not missing notifications*); (5) This notification mechanism provides me the information that I want (*Providing wanted information*).

For *Comfort* and *Comfort with others*, there were no statistically significant main and interaction effects. For *Disturbing*, there were a statistically significant main effect of PLACEMENT and two-way interaction effect of ENVIRONMENT × PLACEMENT. Post hoc test revealed that the *Head-Up Display* placement was significantly more disturbing than the other PLACEMENTS, see Figure 6a. For the rest two scales of the questionnaire, we found a statistically significant main effect of PLACEMENT and no other main and interaction effects. For *Not missing notifications*, post hoc test showed that *Head-Up Display* was significantly less prone to miss notifications in comparison to other PLACEMENTS ($p < .001$) which was in line with the results with *Missed Notification*

Count. Furthermore, *Floating* had significantly higher score than *In-Situ* ($p < .05$). For *Providing wanted information*, the pairwise comparison revealed statistically significant differences between *On-Body* and *Head-Up Display* ($p < .042$), and *On-Body* and *In-Situ* ($p < .001$).

Further Questions. To further evaluate our notification mechanism, we asked participants to rate the *helpfulness* of the suggested responses using a 7-item Likert scale. On average participants were positive about the suggested responses ($M = 5.3$, $SD = 1.5$). Furthermore, a two-way mixed-model ANOVA was conducted to compare the effect of the ENVIRONMENT and the PLACEMENT on the question "I would like to use the notification system in my daily VR experience.", see Table 3 and Figure 6b. This revealed a statistically significant main effect of PLACEMENT. Post hoc test showed statistically significant difference between *Floating* and *Head-Up Display* ($p < .001$), *Floating* and *In-Situ* ($p < .029$), and *On-Body* and *Head-Up Display* ($p < .002$).

Interview Feedback

At the end of the study, we interviewed each participant. All interviews were audio-recorded for later analysis. We transcribed the interviews literally while not summarizing or transcribing phonetically, as suggested by the previous work [3]. To analyze the interviews, two researchers applied a simplified version of qualitative coding with affinity diagramming [14].

Overall, participants had a positive general impression about the system, as they indicated that the notification system was *"comfortable"* (P1, P4, P10) and *"handy"* (P13, P14, P23), and the virtual environments were *"very immersive"* (P5, P6, P12, P14). However, 7 (29%) participants commented on the distracting factor of the cable of the headset. Six participants commented on the tasks: 4 (16.6%) stated that they found the card sorting task hard, while for 2 (8.3%) the ball collection task was easy. 13 (54.2%) participants indicated that they would prefer to take off the headset if there is a need to do a complex task regarding the notification: *"[I would not leave VR if] it is short, but for a mail with multiple paragraphs, I would"* (P3). On the other hand, 11 (45.8%) participants stated that in general, they would not leave VR for a notification: *"When you take the headset off you are not connected with the VR world anymore"* (P23).

To the question about the provided answer possibilities, 6 (25%) were satisfied with the method: *"A short answer during the game is perfect"* (P22). However, 11 (45.8%) participants stated that only two answer possibilities were not enough. 9 (37.5%) participants said that they could imagine using a keyboard to enter text in VR to answer to the notifications. As an alternative to keyboards participants suggested utilizing a controller for gesture text input or free-hand writing (P8, P10, P19, P20, P22, P23). 6 (25%) participants indicated that typing in VR is cumbersome: *"Actually, I would not type in VR, this would be too much struggle and complex"* (P14). 14 (58.3%) participants wanted to have a text-to-speech feature to enable input without using a keyboard.

As further features, P2, P5 and P11 wanted to see notification history while in VR. 10 (41.6%) asked for mute and snooze functionality in case they do not want to be disturbed. Further suggested improvements for the system were haptic (vibration (P2, P19)) or visual (flashlight (P4)) feedback for each notification, possibility to zoom (P3, P18), showing *In-Situ* notification always on the same position (P4) and *Head-Up Display* notifications on the periphery (P18), and using non-primary hand to interact with notifications (P4, P9). For multi-user scenarios, participants (P3, P11, P18) stated that they would like to have an implementation that they can use it in multi-user environments in VR without privacy concern: *"First, I would like to see only the sender, and then I can view the content of the notification on my arm."* (P3). 9 (37.5%) participants asked for a feature to filter notifications based on the triggering application, a sender, and a relation (one-to-one and group chat notifications).

While giving feedback about notification placements, P4 and P21 indicated that notifications in the *In-Situ* position were far away, but not distracting. However, 9 (37.5%) participants stated that they had to walk to be able to read the notifications on this placement. 13 (54.2%) participants said that notifications on the *Head-Up Display* placement were distracting and urgent: *"I needed more time to get back into the task [after notification on the Head-Up Display placement]"* (P3). P6 indicated that *Floating* notifications distracted the VR experience since it was possible to pass through the notifications. P2, P5, P8, and P22 stated that *On-Body* placement is advantageous when a user is doing a task in VR with hands, but otherwise, it was easy to miss notifications on this placement.

DISCUSSION AND LIMITATIONS

The study revealed significant main effects of TASK and PLACEMENT but no significant main effect of ENVIRONMENT. We found that *Head-Up Display* placement results in the lowest *Missed Notification Count* and the shortest *Response Time* followed by the *Floating*, *On-Body* and *In-Situ* placements. The subjective results revealed that displaying notifications on the *Head-Up Display* placement results in the highest noticeability, the strongest feeling of not missing notifications but is also more intrusive and disturbing than the other conditions. Consequently, the *Head-Up Display* placement causes the lowest presence feeling. Since notifications using this placement are displayed directly in front of the user and occupying the lower part of the field of view, participants considered them as the most urgent. Participants preferred receiving notification in VR the least using the *Head-Up Display* placement followed by the *In-Situ* placement.

In-Situ placement results in the highest *Answering Distance*. Consequently, this placement leads to the highest *Missed Notification Count* and the slowest *Response Time*. Participants considered notifications using this placement as the least noticeable and urgent ones. Furthermore, they thought about notification placed on a wall as the ones that can easily be missed and do not provide wanted information. However, participants' feedback revealed that they were not disturbed by the notifications displayed using this placement but by the need to walk to the wall to read them.

Notifications using the *On-Body* and *Floating* placements received the highest *Understandability* score. Participants preferred to receive notification in VR the most through these two placements. While the *Floating* placement was assessed as the most comfortable place to display notifications when a user is alone in VR, participants preferred *On-Body* placement for multi-user VR experiences. *On-Body* placement received the highest *SUS* score followed by the *Floating* placement. Furthermore, participants ranked notifications displayed in the *On-Body* placement as the ones that provide the most wanted information followed by the *Floating* placement. Similarly, *On-Body* placement causes the highest sense of presence followed by *Floating* and *In-Situ*.

While displaying notifications using the *Floating* placement, participants changed their position towards the notification the least. This shows that participants could easily read notifications displayed using this placement. However, as a notification could be displayed while the user is walking, they could walk through the notification which some participants stated as disturbing. On the other hand, using the *On-Body* placement, notifications are attached to the controller, providing users with control over the actual position of the notification. This placement enables participants to move the notification out of their sight to focus on their primary task.

There was a significant effect of the current task in VR on the *Missed Notification Count* and the *Response Time*. While performing the *Gaming* task, participants moved the most within the environment, and it resulted in the fastest *Response Time* and the lowest *Missed Notification Count*. On the other hand, the *Learning* task, which was the most concentration-demanding, caused the highest *Missed Notification Count* and *Response Time*.

Limitations

While we systematically varied the task and the environment to increase the generalizability of the results, the study design causes some limitations. To be able to generalize our results, we used three different virtual environments. However, we did not find a significant main effect of environment. Thus, we consider that more detailed research regarding the content of a virtual environment is needed to acknowledge any effect of it. We used notifications that were not collected from participants. To increase the realism and enable participants to envision how their notifications would appear in VR, we personalized the notifications using participants' contacts. Therefore, we assume that we reduced potential effects caused by not showing participants' notifications. Furthermore, participants indicated that not performing tasks with their hands could result in missing notifications when using the *On-Body* placement. Since we only used visual feedback, we assume that additional visual, auditory, or haptic feedback, as suggested by the participants could make the notifications more noticeable. However, future research is needed to test this assumption as additional feedback can affect the user's sense of presence. Similar to previous work, e.g., Ghosh *et al.* [12], we asked participants to acknowledge notifications. However, participants wished to respond to notifications not only through two predefined responses but also using other approaches, including speech-to-text and free-hand writing. Accordingly, future work should compare different approaches to respond to notifications.

DESIGN RECOMMENDATIONS

Based on the results, we derived the following design recommendations for displaying digital notifications in VR:

Display only urgent notifications using a Head-Up Display. Notifications using the *Head-Up Display* placement are the most intrusive, disturbing, and noticeable ones. Thus, the *Head-Up Display* placement should only be used to display urgent notifications, for which users would accept their negative impact to ensure receiving them.

Show unimportant notifications In-Situ. Notifications displayed using the *In-Situ* placement are the least noticeable and the easiest to miss. Therefore, this placement should be used to display non-essential notifications, as the information can be delivered without interrupting the VR experience.

Use On-Body and Floating placements to display general notifications. Notifications using the *On-Body* and *Floating* placements result in the highest *Understandability*, *SUS* scores, and feeling of presence. Considering that these placements are also the most preferred ones, we conclude that general notification should be displayed using *Floating* and *On-Body* placements. Users should be able to filter notifications to define which notifications are urgent. In addition to defining filters by sender or application, users should also be enabled to specify their preference for the multi-user VR environments.

CONCLUSION

We investigated four notification placements (*Head-Up Display*, *On-Body*, *Floating*, and *In-Situ*) while performing three tasks (*Gaming*, *Learning*, and *ProblemSolving*) in three virtual environments (*Open*, *Semi-Open*, and *Closed*). We found that showing notifications using a *Head-Up Display* placement decreases the response time and the number of missed notifications while increasing noticeability, distraction, and intrusiveness. Displaying notifications using the *In-Situ* placement increases the response time, the amount of missed notifications, and the distance walked to respond to the notifications while decreasing noticeability. *Floating* and *On-Body* placements are the most preferred placements for displaying notifications in VR. Furthermore, we found that showing notifications while performing a concentration-demanding *Learning* task results in the highest number of missed notifications and the highest response time. Conversely, displaying notifications while *Gaming* causes the least number of missed notifications and the shortest response time. Based on the results, we derived design recommendations. As our participants proposed to delay notifications, future work should investigate approaches to "snooze" notifications, as suggested by previous work on mobile notifications [47]. Finally, further research that enables users to respond to notifications without leaving the VR is needed. Quick responses, as provided by current mobile devices, might be a valuable approach.

ACKNOWLEDGMENTS

This work was financially supported by the German Research Foundation (DFG) within Cluster of Excellence in Simulation Technology (EXC 310/2) at the University of Stuttgart and by the German Ministry of Education and Research (BMBF) within the GEVAKUB project (01JKD1701A).

REFERENCES

[1] Ghassem Alaee, Amit P Deasi, Lourdes Pena-Castillo, Edward Brown, and Oscar Meruvia-Pastor. 2018. A User Study on Augmented Virtuality Using Depth Sensing Cameras for Near-Range Awareness in Immersive VR.

[2] Esta A. Berg. 1948. A Simple Objective Technique for Measuring Flexibility in Thinking. *The Journal of General Psychology* 39, 1 (1948), 15–22. DOI: http://dx.doi.org/10.1080/00221309.1948.9918159

[3] Ann Blandford, Dominic Furniss, and Stephann Makri. 2016. *Qualitative Hci Research: Going Behind the Scenes*. Morgan & Claypool Publishers. 1–115 pages. DOI: http://dx.doi.org/10.2200/S00706ED1V01Y201602HCI034

[4] John Brooke. 1996. SUS-A quick and dirty usability scale. *Usability evaluation in industry* 189, 194 (1996), 4–7.

[5] Pulkit Budhiraja, Rajinder Sodhi, Brett Jones, Kevin Karsch, Brian Bailey, and David Forsyth. 2015. Where's My Drink? Enabling Peripheral Real World Interactions While Using HMDs. *arXiv preprint arXiv:1502.04744* (2015).

[6] Soon Hau Chua, Simon T. Perrault, Denys J. C. Matthies, and Shengdong Zhao. 2016. Positioning Glass: Investigating Display Positions of Monocular Optical See-Through Head-Mounted Display. In *Proceedings of the Fourth International Symposium on Chinese CHI (ChineseCHI2016)*. ACM, New York, NY, USA, Article 1, 6 pages. DOI: http://dx.doi.org/10.1145/2948708.2948713

[7] Fulvio Corno, Luigi De Russis, and Teodoro Montanaro. 2017. XDN: Cross-device Framework for Custom Notifications Management. In *Proceedings of the ACM SIGCHI Symposium on Engineering Interactive Computing Systems (EICS '17)*. ACM, New York, NY, USA, 57–62. DOI: http://dx.doi.org/10.1145/3102113.3102127

[8] Amit P Desai, Lourdes Pena-Castillo, and Oscar Meruvia-Pastor. 2017. A Window to Your Smartphone: Exploring Interaction and Communication in Immersive VR with Augmented Virtuality. In *14th Conference on Computer and Robot Vision (CRV '17)*. 217–224. DOI: http://dx.doi.org/10.1109/CRV.2017.16

[9] Tilman Dingler, Kai Kunze, and Benjamin Outram. 2018. VR Reading UIs: Assessing Text Parameters for Reading in VR. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems (CHI EA '18)*. ACM, New York, NY, USA, Article LBW094, 6 pages. DOI: http://dx.doi.org/10.1145/3170427.3188695

[10] Thomas Gaubert. 2016. *Zephyr*. GitHub repository. (2016). https://github.com/ThomasGaubert/zephyr.

[11] Ceenu George, Manuel Demmler, and Heinrich Hussmann. 2018. Intelligent Interruptions for IVR: Investigating the Interplay Between Presence, Workload and Attention. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems (CHI EA '18)*. ACM, New York, NY, USA, Article LBW511, 6 pages. DOI: http://dx.doi.org/10.1145/3170427.3188686

[12] Sarthak Ghosh, Lauren Winston, Nishant Panchal, Philippe Kimura-Thollander, Jeff Hotnog, Douglas Cheong, Gabriel Reyes, and Gregory D. Abowd. 2018. NotifiVR: Exploring Interruptions and Notifications in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 24, 4 (2018), 1447–1456. DOI: http://dx.doi.org/10.1109/TVCG.2018.2793698

[13] Jeffrey I Gold, Katharine A Belmont, and David A Thomas. 2007. The neurobiology of virtual reality pain attenuation. *CyberPsychology & Behavior* 10, 4 (2007), 536–544.

[14] Gunnar Harboe and Elaine M. Huang. 2015. Real-World Affinity Diagramming Practices: Bridging the Paper-Digital Gap. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 95–104. DOI:http://dx.doi.org/10.1145/2702123.2702561

[15] Hsiu-Mei Huang, Ulrich Rauch, and Shu-Sheng Liaw. 2010. Investigating learners' attitudes toward virtual reality learning environments: Based on a constructivist approach. *Computers & Education* 55 (11 2010), 1171–1182. DOI: http://dx.doi.org/10.1016/j.compedu.2010.05.014

[16] Shamsi T. Iqbal and Brian P. Bailey. 2010. Oasis: A Framework for Linking Notification Delivery to the Perceptual Structure of Goal-directed Tasks. *ACM Trans. Comput.-Hum. Interact.* 17, 4, Article 15 (Dec. 2010), 28 pages. DOI: http://dx.doi.org/10.1145/1879831.1879833

[17] Jason Jerald. 2016. *The VR Book: Human-Centered Design for Virtual Reality*. Association for Computing Machinery and Morgan & Claypool, New York, NY, USA.

[18] Kohei Kanamori, Nobuchika Sakata, Tomu Tominaga, Yoshinori Hijikata, Kensuke Harada, and Kiyoshi Kiyokawa. 2018. Obstacle Avoidance Method in Real Space for Virtual Reality Immersion. In *IEEE International Symposium on Mixed and Augmented Reality (ISMAR '18)*. IEEE, 80–89. DOI: http://dx.doi.org/10.1109/ISMAR.2018.00033

[19] Anjuli Kannan, Karol Kurach, Sujith Ravi, Tobias Kaufman, Balint Miklos, Greg Corrado, Andrew Tomkins, Laszlo Lukacs, Marina Ganea, Peter Young, and Vivek Ramavajjala. 2016. Smart Reply: Automated Response Suggestion for Email. In *Proceedings of the ACM SIGKDD Conference on Knowledge Discovery and Data Mining (KDD'16)*. https://arxiv.org/pdf/1606.04870v1.pdf

[20] Romina Kettner, Patrick Bader, Thomas Kosch, Stefan Schneegass, and Albrecht Schmidt. 2017. Towards Pressure-based Feedback for Non-stressful Tactile Notifications. In *Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '17)*. ACM, New York, NY, USA, Article 89, 8 pages. DOI: http://dx.doi.org/10.1145/3098279.3122132

[21] Thomas Kubitza, Alexandra Voit, Dominik Weber, and Albrecht Schmidt. 2016. An IoT Infrastructure for Ubiquitous Notifications in Intelligent Living Environments. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct (UbiComp '16)*. ACM, New York, NY, USA, 1536–1541. DOI: http://dx.doi.org/10.1145/2968219.2968545

[22] Owlchemy Labs. 2016. *Job Simulator: The 2050 Archives*. Game [Microsoft Windows, PlayStation 4]. (5 April 2016). Owlchemy Labs.

[23] Wolf & Wood Interactive Ltd. 2016. *A Chair in a Room : Greenwater*. Game [Microsoft Windows]. (5 April 2016). Wolf & Wood Interactive Ltd, UK.

[24] Mark McGill, Daniel Boland, Roderick Murray-Smith, and Stephen Brewster. 2015. A Dose of Reality: Overcoming Usability Challenges in VR Head-Mounted Displays. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 2143–2152. DOI:http://dx.doi.org/10.1145/2702123.2702382

[25] Jason Orlosky, Kiyoshi Kiyokawa, and Haruo Takemura. 2014. Managing Mobile Text in Head Mounted Displays: Studies on Visual Preference and Text Placement. *SIGMOBILE Mob. Comput. Commun. Rev.* 18, 2 (June 2014), 20–31. DOI: http://dx.doi.org/10.1145/2636242.2636246

[26] Martin Pielot, Karen Church, and Rodrigo de Oliveira. 2014. An In-situ Study of Mobile Phone Notifications. In *Proceedings of the 16th International Conference on Human-computer Interaction with Mobile Devices & Services (MobileHCI '14)*. ACM, New York, NY, USA, 233–242. DOI: http://dx.doi.org/10.1145/2628363.2628364

[27] Martin Pielot and Luz Rello. 2015. The Do Not Disturb Challenge: A Day Without Notifications. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '15)*. ACM, New York, NY, USA, 1761–1766. DOI: http://dx.doi.org/10.1145/2702613.2732704

[28] Martin Pielot and Luz Rello. 2017. Productive, Anxious, Lonely: 24 Hours Without Push Notifications. In *Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '17)*. ACM, New York, NY, USA, Article 11, 11 pages. DOI: http://dx.doi.org/10.1145/3098279.3098526

[29] Martin Pielot, Amalia Vradi, and Souneil Park. 2018. Dismissed!: A Detailed Exploration of How Mobile Phone Users Handle Push Notifications. In *Proceedings of the 20th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '18)*. ACM, New York, NY, USA, Article 3, 11 pages. DOI: http://dx.doi.org/10.1145/3229434.3229445

[30] Elizabeth Quinn and Ian Stephen Paul Nation. 1974. *Speed reading: A course for learners of English*. Oxford University Press.

[31] Sylvia Rothe, Kim Tran, and Heinrich Hussmann. 2018. Dynamic Subtitles in Cinematic Virtual Reality. In *Proceedings of the 2018 ACM International Conference on Interactive Experiences for TV and Online Video (TVX '18)*. ACM, New York, NY, USA, 209–214. DOI: http://dx.doi.org/10.1145/3210825.3213556

[32] Rufat Rzayev, Paweł W. Woźniak, Tilman Dingler, and Niels Henze. 2018. Reading on Smart Glasses: The Effect of Text Position, Presentation Type and Walking. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 45, 9 pages. DOI: http://dx.doi.org/10.1145/3173574.3173619

[33] Alireza Sahami Shirazi, Niels Henze, Tilman Dingler, Martin Pielot, Dominik Weber, and Albrecht Schmidt. 2014. Large-scale Assessment of Mobile Notifications. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. ACM, New York, NY, USA, 3055–3064. DOI: http://dx.doi.org/10.1145/2556288.2557189

[34] Stefan Schneegass and Rufat Rzayev. 2016. Embodied Notifications: Implicit Notifications Through Electrical Muscle Stimulation. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct (MobileHCI '16)*. ACM, New York, NY, USA, 954–959. DOI:http://dx.doi.org/10.1145/2957265.2962663

[35] Susan M. Schneider, Cassandra K. Kisby, and Elizabeth P. Flint. 2011. Effect of virtual reality on time perception in patients receiving chemotherapy. *Supportive Care in Cancer* 19, 4 (01 Apr 2011), 555–564. DOI: http://dx.doi.org/10.1007/s00520-010-0852-7

[36] Guy Schofield, Gareth Beale, Nicole Beale, Martin Fell, Dawn Hadley, Jonathan Hook, Damian Murphy, Julian Richards, and Lewis Thresh. 2018. Viking VR: Designing a Virtual Reality Experience for a Museum. In *Proceedings of the 2018 Designing Interactive Systems Conference (DIS '18)*. ACM, New York, NY, USA, 805–815. DOI: http://dx.doi.org/10.1145/3196709.3196714

[37] Thomas Schubert, Frank Friedmann, and Holger Regenbrecht. 2001. The experience of presence: Factor analytic insights. *Presence: Teleoperators & Virtual Environments* 10, 3 (2001), 266–281.

[38] Lior Shapira and Daniel Freedman. 2016. Reality Skins: Creating Immersive and Tactile Virtual Environments. In *IEEE International Symposium on Mixed and Augmented Reality (ISMAR '16)*. 115–124. DOI: http://dx.doi.org/10.1109/ISMAR.2016.23

[39] Ludwig Sidenmark, Nicolas Kiefer, and Hans Gellersen. 2019. Subtitles in Interactive Virtual Reality: Using Gaze to Address Depth Conflicts. In *Workshop on Emerging Novel Input Devices and Interaction Techniques*.

[40] Adalberto L. Simeone, Eduardo Velloso, and Hans Gellersen. 2015. Substitutional Reality: Using the Physical Environment to Design Virtual Reality Experiences. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 3307–3316. DOI:http://dx.doi.org/10.1145/2702123.2702389

[41] Misha Sra, Sergio Garrido-Jurado, Chris Schmandt, and Pattie Maes. 2016. Procedurally Generated Virtual Reality from 3D Reconstructed Physical Space. In *Proceedings of the 22Nd ACM Conference on Virtual Reality Software and Technology (VRST '16)*. ACM, New York, NY, USA, 191–200. DOI: http://dx.doi.org/10.1145/2993369.2993372

[42] Bethesda Game Studios. 2018. *The Elder Scrolls V: Skyrim VR*. Game [Microsoft Windows]. (3 April 2018). Bethesda Softworks.

[43] Ubisoft and Red Storm Entertainment. 2017. *Star Trek: Bridge Crew*. Game [PlayStation 4, Microsoft Windows]. (30 May 2017). Ubisoft and Red Storm Entertainment.

[44] Alexandra Voit, Tonja Machulla, Dominik Weber, Valentin Schwind, Stefan Schneegass, and Niels Henze. 2016. Exploring Notifications in Smart Home Environments. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct (MobileHCI '16)*. ACM, New York, NY, USA, 942–947. DOI: http://dx.doi.org/10.1145/2957265.2962661

[45] Dominik Weber, Sven Mayer, Alexandra Voit, Rodrigo Ventura Fierro, and Niels Henze. 2016. Design Guidelines for Notifications on Smart TVs. In *Proceedings of the ACM International Conference on Interactive Experiences for TV and Online Video (TVX '16)*. ACM, New York, NY, USA, 13–24. DOI: http://dx.doi.org/10.1145/2932206.2932212

[46] Dominik Weber, Alireza Sahami Shirazi, and Niels Henze. 2015. Towards Smart Notifications Using Research in the Large. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct (MobileHCI '15)*. ACM, New York, NY, USA, 1117–1122. DOI: http://dx.doi.org/10.1145/2786567.2794334

[47] Dominik Weber, Alexandra Voit, Jonas Auda, Stefan Schneegass, and Niels Henze. 2018b. Snooze!: Investigating the User-defined Deferral of Mobile Notifications. In *Proceedings of the 20th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '18)*. ACM, New York, NY, USA, Article 2, 13 pages. DOI: http://dx.doi.org/10.1145/3229434.3229436

[48] Dominik Weber, Alexandra Voit, and Niels Henze. 2018a. Notification Log: An Open-Source Framework for Notification Research on Mobile Devices. In *Proceedings of the 2018 ACM International Joint Conference and 2018 International Symposium on Pervasive and Ubiquitous Computing and Wearable Computers (UbiComp '18)*. ACM, New York, NY, USA, 1271–1278. DOI: http://dx.doi.org/10.1145/3267305.3274118

[49] Dominik Weber, Alexandra Voit, Gisela Kollotzek, Lucas van der Vekens, Marcus Hepting, Florian Alt, and Niels Henze. 2018c. PD Notify: Investigating Personal Content on Public Displays. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems (CHI EA '18)*. ACM, New York, NY, USA, Article LBW014, 6 pages. DOI: http://dx.doi.org/10.1145/3170427.3188475

[50] Bob G. Witmer, Christian J. Jerome, and Michael J. Singer. 2005. The Factor Structure of the Presence Questionnaire. *Presence: Teleoperators and Virtual Environments* 14, 3 (2005), 298–312. DOI: http://dx.doi.org/10.1162/105474605323384654

[51] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. 2011. The Aligned Rank Transform for Nonparametric Factorial Analyses Using Only Anova Procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 143–146. DOI: http://dx.doi.org/10.1145/1978942.1978963

[52] André Zenner, Marco Speicher, Sören Klingner, Donald Degraen, Florian Daiber, and Antonio Krüger. 2018. Immersive Notification Framework: Adaptive & Plausible Notifications in Virtual Reality. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems (CHI EA '18)*. ACM, New York, NY, USA, Article LBW609, 6 pages. DOI: http://dx.doi.org/10.1145/3170427.3188505