BANS: Evaluation of Bystander Awareness Notification Systems for Productivity in VR

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***Abstract*—VR Head-Mounted Displays (HMDs) provide unlimited and personalized virtual workspaces and will enable working anytime and anywhere. However, if HMDs are to become ubiquitous, VR users are at risk of being observed, which can threaten their privacy. We examine six Bystander Awareness Notification Systems (BANS) to enhance VR users' bystander awareness whilst immersed in VR. In a user study (N=28), we explore how future HMDs equipped with BANS might enable users to maintain their privacy while contributing towards enjoyable and productive travels. Results indicate that BANS increase VR users' bystander awareness without affecting presence and productivity. Users prefer BANS that extract and present the most details of reality to facilitate their bystander awareness. We conclude by synthesizing four recommendations, such as providing VR users with control over BANS and considering how VR users can best transition between realities, to inform the design of privacy-preserving HMDs.**

I. Introduction

Virtual reality (VR) will enable individualized and large-scale virtual workspaces to be accessed anytime and anywhere. Meta's Infinite Office [48], Virtual Desktop [87] and vSpatial [90] already enable VR users to work inside of virtuality across multiple, customizable displays without being bound to a traditional physical office (e.g., working while being in a car [36], on a plane [58], or on a train [54]). The use of virtual, location agnostic workspaces can be particularly beneficial for people who frequently travel (e.g., to raise work-life balance). In 2019, an average one-way commute in the United States increased to a new high of over 27 minutes, with 9.8% of commuters reporting a daily one-way commute of at least one hour [8]. In Europe, more than 95% of employees commute between their home and work with 34.4% spending more than 30 minutes on their daily one-way commute [14]. There are only 4.3% of EU employees who are not required to travel for work [14]. Due to the considerable amount of time people spend in transit, a lot of their time cannot be used efficiently [39]. To work towards a future where commuting can be efficiently used for productivity, early work by McGill et al. [51], Medeiros et al. [54], Ng et al. [58] and Gugenheimer et al. [29] explored how VR can support (and sometimes even enable) productivity in transit.

Whilst Pritchard [71], Schneider et al. [77] and Otte et al. [66] have investigated how peripheral devices (e.g., physical keyboards) can be integrated and used in VR to enhance VR users' productivity, VR usage in public environments presents unique challenges [17, 29, 42]. VR users are generally not aware of their surroundings [49, 59] and bystanders may observe the VR user's interactions [9, 60, 67], which can be particularly problematic when VR users interact with and provide sensitive data. Such observations can interfere with a VR user's productivity [22] and can provide bystanders with different types of personal information (e.g., passwords, addresses). The existing literature highlights the ease of bystanders identifying the VR user's task type within seconds [22]. Even worse, prior work showed how easy it is to observe VR users' input of personal information, including traditional touch/VR controller mid-air gestures [21, 44, 65].

We investigate, for the first time, means to support VR users in their awareness of potential privacy invasions whilst working on productivity tasks during their travels. We implemented six Bystander Awareness Notification Systems (BANS) that represent bystanders at different levels of the Milgram's reality-virtuality continuum [55] to increase VR users' awareness of potential privacy-critical observations (e.g., a bystander observing password input on a physical keyboard). The studied BANS, which are mapped onto a "Reality Awareness Continuum" at different levels (cf. Figure 1), visualized in Figure 2 and described in Section III, are: (a) Text UI, (b) Avatar, (c) 2D-Radar (d) Attention Marker, (e) 3D-Scan and (f) Passthrough. We evaluated the BANS' usability, their impact on the VR users' sense of presence and the overall VR experience in an in situ user study with 28 participants.

We found that the studied BANS provide VR users with a reasonably high sense of privacy without negatively affecting their productivity or sense of presence while immersed in VR. However, although 3D-Scan, a 1:1 representation of the real-world bystander in VR, was the most preferred BAN (Section VI-F), the bigger picture shows increased reality awareness may not always be preferred. For example, BANS which present VR users with the least amount of information about the real environment (e.g., Text UI) were preferred over

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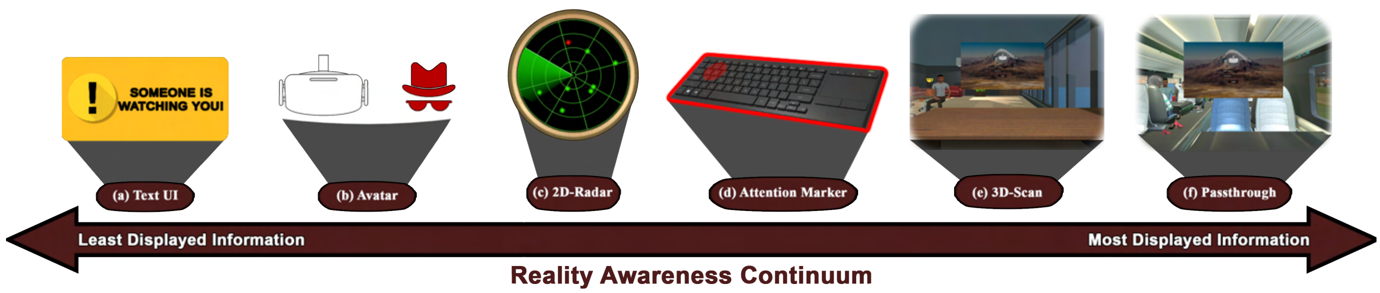

Fig. 1. We explore the use of BANS to support VR users' privacy in public. We compare the usability of different BANS, i.e., from least to most displayed information, and their impact on VR users' productivity and sense of presence. Figures (a) to (f) illustrate the BANS, described in more detail in Section III.

systems that provide VR users with more details of reality (e.g., Attention Marker, Passthrough, Avatar). This suggests the information extracted from reality should be presented in a straightforward, diegetic manner to avoid confusion and to not disrupt users' productivity in VR. Based on our findings, we synthesize four recommendations, such as providing VR users with control over BANS and considering how VR users can best transition between realities, to inform researchers working on future virtual workspaces about how to design effective and privacy-preserving VR experiences while traveling.

Contribution Statement. The contribution of this paper is threefold: **(1)** We complement prior work that explored bystander awareness systems and how to facilitate productivity in public spaces by the first lab study that evaluates the effect of BANS on users' sense of privacy and productivity while performing productivity tasks in VR; **(2)** We present the results from a user study (N=28) highlighting the effect of information granularity displayed by the different BANS on VR users' sense of presence and privacy perception; **(3)** Finally, we derive recommendations for the design of future privacy-preserving HMDs to support VR users in protecting their privacy during VR experiences in public.

II. Related Work

Our concept of BANS is influenced by prior research on VR productivity in mobile, stationary and public environments and on VR bystander awareness systems.

A. VR Usage in Public and for Productivity Tasks

The introduction of standalone HMDs like the HTC Vive Focus and the Oculus Quest 2 facilitates the use of HMDs in public spaces, and a large body of work has already begun to investigate a potential future of the use of VR in public and shared spaces [28, 29, 37, 38, 40, 76, 80]. For example, using VR for multi-display workspaces [58] while being on a plane or for more general in-flight entertainment [92]. However, the use of VR in public introduces unique challenges [51, 92] as impediments that prevent safe usage and function due to motion sickness, and limit interactions in constrained spaces. The society's current lack of social acceptability for public VR usage, among many other challenges, further prevents the widespread adoption of VR usage in public [51, 92]. To overcome such issues, Schmelter and Hildebrand [76] suggested VR applications should be designed for comfort and safety while allowing users to have an enjoyable experience in confined spaces. McGill et al. [49] proved that incorporating reality into VR could help VR users interact with objects in reality, and suggested the amount of reality displayed in the virtuality should be limited to what is necessary to facilitate interaction across realities [49]. Knierim et al. [32, 33] and Fereydooni and Walker [17], meanwhile, presented opportunities and challenges associated with using HMDs as virtual offices. One such challenge was enabling efficient text input in VR, a fundamental requirement for effortlessly performing productivity tasks. Knierim et al. [31] and Grubert et al. [26] introduced multiple solutions to facilitate VR text entry by visualizing physical keyboards in VR to enhance VR users' text input experience, which contributed towards the consumer solutions now available for enhanced productivity in VR (e.g., Oculus' Tracked Keyboard SDK[1] which renders users' hands on top of a VR representation of the physical keyboard in VR).

In addition to text entry, others have championed the benefits of VR for enabling revolutionized workspaces [50]. Mcgill et al. [50] explored the use of multi-display workspaces in VR and developed new ways of minimizing users' physical effort and discomfort while interacting with virtual displays in VR. They found implicit control of display position based on head orientation provides significant benefits in terms of user preference, workload and user comfort, contributing towards improved comfort and ease of use for productivity tasks in VR. To enhance people's productivity in transit, Ng et al. [58] investigated multi-display workspaces inside of VR and examined how public transit influences VR users' preferences of multi-display layouts. They found that users prefer display layouts that remain within their personal space/seating area rather than in the surrounding shared space. In a different form of transportation, Li et al. [37] examined productivity tasks in VR in the rear seat of a car to understand how physical

[1] https://developer.oculus.com/documentation/unity/tk-overview/, accessed 13/09/2022

constraints in transportation and virtual working spaces affect users' performance. They found that creating virtual borders helps users adjust to the confined area in transportation.

Overall, a large body of work has discussed and investigated the use of VR HMDs for productivity in public and social spaces, particularly while traveling. Our motivation of studying BANS for productivity in VR and the research presented in this paper draws from these works.

B. VR Bystander Awareness

The loss of VR users' informal awareness of nearby persons in their surrounding environment has motivated the HCI and usable security research communities to design, implement and evaluate BANS. BANS support VR users in remaining aware of their surroundings while staying engaged in their VR experience. They extract varying degrees of information from the real world and contextually deliver it to a VR user [59], to which we refer as the "reality-awareness continuum" (cf. Figure 1). The continuum ranges from no incorporated awareness of reality (e.g., no BANS, the current state-of-the-art of VR headsets) to complete awareness of reality (e.g., Passthrough [89]). The more information BANS capture from the reality and incorporate into virtuality, the more likely VR users are aware of their real-world surroundings.

McGill et al. [49] were the first to consider how to increase VR users' awareness of their real-world surroundings by investigating interactions across realities using a bystander awareness system with two states: low and high engagement. These states support VR users' awareness of other people (i.e., bystanders) in the same physical space by fading them into the virtual environment and fully blending them when VR users wish to engage with them. Blending reality into virtuality allows VR users to perform basic social interaction with bystanders without having to leave VR. While McGill et al.'s [49] approach displayed information from the reality inside of virtuality and provided a high level of bystander awareness, they argued that this form of visualization profoundly disrupts VR users' sense of presence and recommended future approaches to be less disruptive. In response to McGill et al.'s [49] work, Ghosh et al. [24] explored how notifications can be delivered to users in VR along with bystander visualization methods to help build VR users' awareness of the real world while maintaining their immersion in VR. They developed two notification systems relaying varying amounts of real-world information to notify users of bystanders [24]. Their findings align with work by McGill et al.: even though the system that depicted more information from the reality was more noticeable, it was considered too intrusive and disruptive to the VR user's experience [24].

To help balance VR immersion and bystander awareness, Kudo et al. [35] tested three bystander visualization techniques, depicting the same amount of information from the reality. Each visualization technique showed if a bystander is present, their proximity to the VR user and if they are facing the VR user. Their results showed it is possible to establish bystander awareness without excessively disrupting users' immersion [35]. Gottsacker et al. [25], meanwhile, developed five notifications which conveyed varying amounts of real-world information to explore how the amount of information relayed affects cross-reality interruptions and found users preferred diegetic-based notifications to provide cross-reality interruptions. There are many more works that have proposed and investigated the design of BANS to maintain users' VR experience whilst providing some level of increased bystander awareness (e.g., [23, 53, 59, 61, 62, 64, 82, 88, 92, 94]), highlighting the need of reality aware HMDs that provide VR users' with some sense of reality, and awareness of bystanders, without negatively impacting their VR experience.

C. Summary

The use of VR HMDs in public spaces is becoming ubiquitous, but there is a lack of research focusing on corresponding privacy challenges, one of which is aiding VR users in maintaining bystander awareness while preserving their sense of presence and contributing towards enjoyable VR experiences. Whilst prior research has examined the usage of BANS to facilitate cross-reality interactions and bystander awareness [24, 25, 35, 49, 59, 88], the utility of BANS to protect users' privacy in realistic VR productivity tasks (i.e., in situ) remains unexplored. Although the VR content itself is rendered through a private visual channel which is not visible to bystanders, privacy is still not guaranteed as shown by previous works [21, 22, 44, 65]. Bystanders can easily observe users during input, for example, during authentications or writing confidential emails, compromising VR users' privacy. Therefore, this work advances research on reality aware VR HMDs by combining research on BANS with realistic applications and explores, for the first time, the usability and impact of different BANS on VR users' privacy perception during productivity tasks in public spaces. Although existing research has highlighted the advantages of VR usage in public for a variety of productivity tasks to, for example, interact with virtual displays in VR [37, 54, 58], it is important to address potential privacy concerns before deploying VR HMDs on a larger scale for use in public.

III. Exploring the Concept of Bystander Awareness Notification Systems (BANS)

An initial lightweight literature review on bystander awareness systems was conducted to define an initial design space of BANS that is suitable for the first investigation of BANS and the users' privacy perceptions. We conducted three informal brainstorming sessions with four authors on Miro[2], an online visual collaboration platform, to discuss and expand on the initial BANS. Based on the discussions and the existing literature [35, 49, 59, 61, 82, 89], seven BANS (including a baseline) were implemented in VR, all of which provide different levels of reality awareness and are situated at different levels on the bystander awareness continuum. Figure 1 provides an overview of all studied BANS and Figure 2 shows

[2]https://miro.com/, last accessed 31/10/2022

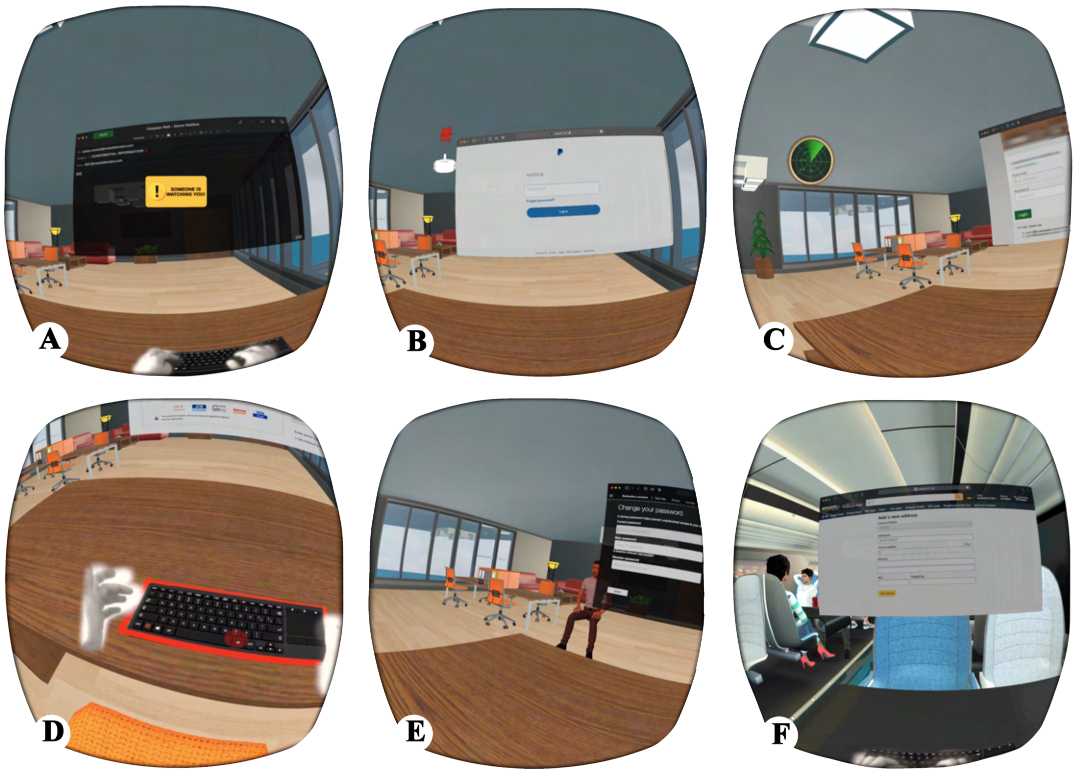

Fig. 2. Snippets of the six BANS: **A)** Text UI, **B)** Avatar, **C)** 2D-Radar, **D)** Attention Marker, **E)** 3D-Scan, **F)** Passthrough.

the same BANS in a virtual workspace environment. Auditory feedback (i.e., a "beep tone") was included in all BANS as a modality to direct users' attention to the visual notifications, as suggested by Ghosh et al. [24]. All BANS were triggered automatically after a five second VR experience, similar to previous works [25, 59]. Each notification stayed visible for up to ten seconds before disappearing automatically.

The BANS were designed to allow for intentionally dismissing them by continuing with the VR productivity task (i.e., typing on the physical keyboard). Introducing an intentional dismissal feature for all BANS provides VR users with full control of the BANS and is a common approach when designing and implementing notification systems [91] and has previously been identified as future work when designing notification systems for VR [74]. A buffer of three seconds (determined through pilot tests) was used to lock manually dismissing the notification and to allow VR users to perceive the notification and not accidentally dismiss it. The following six BANS were implemented to evaluate their usability and impact on the VR users' productivity and perceived sense of presence. All implementations are inspired by previous research on bystander awareness [35, 49, 59, 61, 82, 89]:

- **Text UI (A)** In this bystander awareness system, a notification appears in the middle of the VR user's field of view to inform them about observations. The notification was egocentric so as to reduce the visual search. In the design, we used yellow as color and an exclamation mark to grab the user's attention [13, 20]. This system was designed to reveal the least amount of information about the real-world environment and is based on previous work on text notifications in VR [59].
- **Avatar (B)** Based on Kudo et al. [35], a white VR headset icon was used to represent the VR user and a red avatar symbol of the bystander who observed (and triggered the BAN) was used to represent the observer. The colors white and red were used to convey neutrality (VR user) and potential privacy concerns (bystander observing the VR user) [13]. The avatar was displayed at an egocentric position, namely the upper left corner. The positioning of the notification was chosen to not cover or interfere with the user's productivity task in VR. This BAN system reveals an approximate position of the potential observer. The observer's icon is either positioned to the right, left, above or under the VR headset symbol, depending on the position of the observer.
- **2D-Radar (C)** Inspired by Kudo et al.'s mini-map [35] and Simeone et al. [82], an egocentric 2D-Radar BAN system was displayed at the upper left corner of the VR users' field of view. Any physical bystanders are visualised on the radar, either as "passive" bystander (green dot) or as observer (red dot). The bystanders' positions (i.e., the dots in the radar) are updated every two seconds to provide VR users with real-time data and account for changes in the real-world environment. The 2D-Radar included proximity rings to help VR users in estimating the proximity to the observer.
- **Attention Marker (D)** This BAN system is displayed on a potential VR input method, i.e., a keyboard in the virtual world space, which will likely be widely adopted when

using VR for productivity tasks (e.g., Logitech's Illuminated Keyboard K830, combined with Oculus' Tracked Keyboard SDK [11]). A red flashing border appears around the input device (i.e., keyboard), accompanied by a red translucent circle overlaying the part of the device observed by the bystander. In line with the Avatar BAN, red was used to grab attention [13].

- **3D-Scan (E)** Inspired by the "Partial Blending" [49], the observer is only visualized in virtuality without any additional contextual information of the real world. The visualization of the observer matches the actual size and spatial position of them in the real world. Once the 3D Scan appears, it starts flashing in red to aid the user in distinguishing it from the virtual environment [3, 70].
- **Passthrough (F)** This BAN system enables users to see the real-world surroundings through the VR HMD's cameras while overlaying the virtual elements required for the productivity task. It represents an AR experience where VR users have full access to the real-world surroundings while specific virtual objects, e.g., the virtual displays and keyboard, are still visible, emulating the Oculus Quest 2 MR Passthrough functionality [89].

A. *Studied VR Experiences: Productivity Tasks*

To evaluate the different BANS in realistic scenarios, we implemented seven tasks that participants had to perform in VR. The tasks were designed to include the entry of privacy-sensitive information (e.g., passwords, addresses and credit card information) using a physical keyboard as peripheral device. We opted for keyboard input as this is the most common peripheral device when performing a productivity task and because keyboard input in VR has received significant attention by the VR research community [50, 52]. Role-playing was applied to the task designs to contribute towards creating a more realistic experience for participants [34, 75, 85]. Participants created their own virtual identity they used throughout the entire study through a traditional login screen. This virtual identity aided in making the tasks more realistic by adding a layer of data verification, allowing participants to proceed only if they enter the correct data. Furthermore, the user would perceive potential observations as more endangering because of their attachment to this virtual identity [93].

All tasks were designed to create a similar experience across the conditions, thus supporting a fair comparison and contributing towards internal validity. The following VR experiences were used in the study to simulate productivity in VR (cf. Appendix C for the user interfaces).

Task #1: Windows Login: Participants were asked to login to a windows system using the credentials of their virtual identity. The username is cross-checked with the username they entered in the welcome screen. The password they enter in this task will be used for authentication in the following task. After verifying the credentials, participants were asked to enter a predefined PIN. No prior knowledge of a Windows machine was required as participants were exposed to a traditional login screen that requires a username and a password.

Task #2: Change Email Password: In this task, participants were tasked to change their password of their virtual identity through their email service provider. The new password must have a minimum length of eight characters. Participants had to repeat the new password and confirm it with the PIN code given to them beforehand.

Task #3: Send an Email In this task, participants were asked to send an email that contained confidential information (PIN) to one of their co-workers. A length constraint was added to the content of the email to ensure that participants invest time in preparing the email. The participants' username was displayed in the sender's field of the email to make the task more realistic. The subject field of the email contained design elements to convey the importance of the confidentiality of the email [13, 20]. Note that while we do not encourage people to share any type of PINs or passwords in plain text, we used the sharing of a PIN as an example of confidential information that could be shared via email, which is unfortunately common practice when using online services [5].

Task #4: Login to Paypal: Participants logged into an online financial service using their credentials. To increase the length of the productivity task and align it with the previous tasks, a second authentication factor, a security question, was required to answer as well.

Task #5: Add Address to Amazon Participants filled in five fields containing personal information and address. This depicts the scenario where someone adds personal information (e.g., name, address, telephone number) to one of their online shopping accounts.

Task #6: Login to University Portal In this task, participants used their credentials to logging into a university portal and access potential study material. Participants had to identify their identity by typing an eight digit matriculation number of their choice.

Task #7: Book a Flight Participants were presented with a "Check-out" page of an airline where they had to provide credit card details to finalize their purchase of air travel. The security code of the credit card (e.g., "456") was given to the participants prior to the task.

IV. Implementation and Apparatus

To evaluate the different BANS we implemented a virtual environment (the virtual workspace for productivity tasks) and a simulated reality (a train environment) using the Unity gaming engine and C# [30]. The reality was simulated inside VR, similar to prior works [2, 19, 41, 43, 58]. Our implementation followed Slater et al.'s [84] idea of nested (virtual) realities, with two levels: Simulated Reality and (Simulated) Virtuality [27]. We used an Oculus Quest 2 VR headset, a single fast-switch LCD display with a refresh rate of 90 Hz and a resolution of 1832 $\times$ 1920 pixels per eye. The Logitech Illuminated Keyboard K830 was used for text input during the VR experiences. The keyboard is represented in VR with a 1:1 model matching the position and orientation of the keyboard in reality using Oculus' Tracked Keyboard SDK [11] (cf., Figure 2).

A. Bystander Awareness Notification Systems

During the VR experiences described in Section III-A, the BANS were tested along with a baseline condition, i.e., no BAN system, requiring the user to establish bystander awareness without being aided by the VR headset. We based our implementations on prior work (e.g., [35, 59, 62]) as mentioned in Section III. The BANS triggered after five seconds of being exposed to each productivity task (determined through pilot tests) to represent a bystander observation and contribute towards reliability and internal validity of the first evaluation of the impact of BANS on VR experiences. Using predefined times to simulate bystanders is a common approach in user-centered research [25, 59]. The notifications triggered by the BANS remained visible for up to ten seconds and then disappeared. As described in Section III, a dismissal feature was implemented to allow VR users to manually deactivate the notification by continuing the productivity task. By typing any character on the keyboard the awareness notification disappears. This behavior was implemented for all BANS.

B. Study Environments

Two virtual environments were implemented to a) represent reality (the train, Figure 3) and b) provide participants with a VR environment within a simulated reality (the virtual office, cf., Figure 2). The environments were implemented to present users with a plausible train scenario (reality) and virtual workspace scenario (virtuality) [83]. The study environments, including the implemented BANS and the productivity tasks, are publicly available under https://github.com/shadyemansour/bystander_awareness/.

1) Simulated Reality: Train: To recreate the experience of commuting in public transportation, we used a virtual environment of a train interior with a high level of visual fidelity [68]. We added perceived motion of the virtual train using looped videos of houses and landscape to accurately simulate commuting with an intercity train. To replicate a scenario closer to reality, animated virtual avatars were added in the train environment using Adobe's Mixamo library [56]. We used 14 different characters with a high level of visual fidelity. Each avatar represented a different human behavior that a person would normally do on a train (e.g., conversing, laughing, sleeping, reading and typing on a laptop) to make them appear more authentic. Furthermore, we used a high-fidelity 3D Model of the Oculus Quest 2 (cf. Figure 3) to represent the HMD in the simulated reality. The virtual HMD could be grabbed like a real VR headset in reality to enter the VR experience.

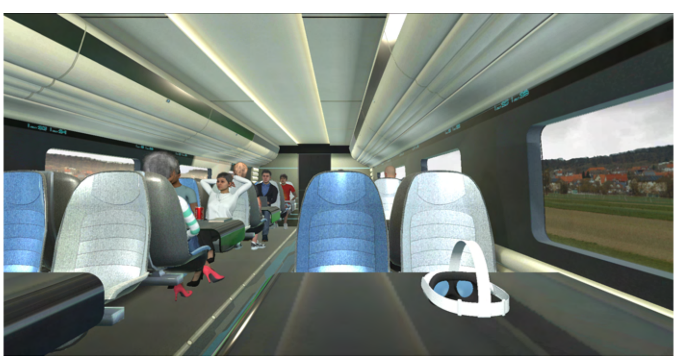

Fig. 3. Simulated reality: The simulated train environment showing the virtual VR HMD used to enter the (nested) VR experience.

2) Virtual Reality: Office: The virtual office is a virtuality nested one level deeper than the simulated reality inside VR. We used publicly available 3D models to furnish the office [15]. It simulated a comfortable real-world office environment. As monitor, we implemented a flat display which measured 800 × 450 pixels and was placed 2.9 m away from the user to ensure comfortable reading [12].

V. Methodology

Building upon related work using VR as a research platform to represent real-world scenarios and investigate user behavior comparable to the real world [2, 41, 43, 58], we used VR to allow users to perform productivity tasks in VR in public transportation. Using VR to simulate tasks in public spaces, specifically public transportation, is used vastly in the field of HCI [19, 58]. VR headsets are not yet equipped with BANS that would allow for in-depth investigations in uncontrolled settings. Furthermore, building eight customized VR headsets with BANS and deploying them in the wild likely introduces confounding variables, not allowing for in-depth foundational research on the usability and feasibility of BANS to inform VR users' about potential threats to their privacy. As a result, we opted to simulate reality and virtuality inside of VR, as done in previous works by Gruenefeld et al. [27], Medeiros et al. [54], Ng et al. [58], among many others. The study complied with the statutory disclosure duty for the collection of data act 13 GDPR at the University of the Bundeswehr Munich. Participants provided written informed consent before participating in the study and were compensated according to the local standard of participant reimbursement (10 EUR).

A. Study Design

The lab study followed a within-subjects experimental design. Participants were exposed to a simulated in-the-wild scenario (similarly to [46, 47, 54, 58], cf., Figure 2 and Figure 3). The BANS were presented in a counterbalanced order using a full Latin square to prevent any potential sequence effects [6]. We had one independent variable, which was the *Bystander Awareness Notification Systems (BANS)* with seven levels: Text UI, Avatar, 2D-Radar, Attention Marker, 3D-Scan and Passthrough. A baseline condition, a VR productivity experience without any BAN system formed the seventh level. An overview of the BANS is shown in Figure 1 and in Figure 2. The dependent variables were task completion time, i.e., the ratio of outputs over input, where the input is the time and the output is the successful completion of the task [71] (based on the efficiency measure of the standard ISO 9241-11[3],

[3]https://www.iso.org/obp/ui/#iso:std:iso:9241:-11:ed-2:v1:en

represented through a user's task completion time), perceived sense of presence and the perceived usability and privacy of HMDs equipped with BANS. To measure the sense of presence we used the iGroup presence questionnaire (IPQ) [78, 79, 81]. The System Usability Scale (SUS) was used to measure the usability of the BANS [7]. Semi-structured interviews (cf., Appendix B) were conducted after the participants experienced all BANS and productivity tasks.

B. Study Task and Procedure

After signing up for the study and providing consent, participants were asked to fill in a form containing a demographics questionnaire to collect age, gender and previous VR experience along with the Affinity for Technology Interaction (ATI) scale [18]. ATI Scores were collected to help facilitate future replication studies. We introduced participants to the study setup, the aim of the study, the different productivity tasks and to the BANS using a slide deck. Participants then put on the physical Oculus Quest 2, which simulated the train reality. After getting familiar with the simulated reality, participants grabbed the virtual Oculus Quest 2 HMD within the simulated reality to enter a personalized virtual office. Participants then began with the first productivity task (see Section III-A) and were presented with one of the BANS (see Section III).

After each task, participants filled in a set of questionnaires. We kept participants in the nested realities (i.e., in VR) to not break their VR experience and to not require them to take off the headset several times during the study [72]. Participants were then asked to fill out the Likert scale questions on a virtual screen in front of them. We used the IPQ [78] and the SUS [7] to learn more about the BANS' impact on participants' sense of presence and participants' perceived usability of the notification systems. Three additional 7-point Likert scale questions were asked to learn more about the BANS' Noticeability, Understandability and Perceived Intrusiveness [24]. After the completion of the questionnaires, the participants were instructed to grab the virtual Oculus Quest 2 headset within VR to enter the virtual office and continue with the next productivity task. After being exposed to the six BANS and one VR productivity experience without a BAN system (baseline), semi-structured interviews were conducted. Participants had the chance to comment on their experience and rank the BANS in terms of usability, privacy and combined usability and privacy. The study concluded with a debriefing of the study.

C. Demographics

We recruited 28 participants (9 females and 19 males), aged 20 to 48 years (M=24.46, SD=5.22), through social media and internal mailing lists. Choosing 28 participants allowed perfectly counterbalancing the independent variable (the BANS) to minimize learning effects. Participants had an ATI Score ranging from 2.8 to 5.89 (M=4.35, SD=0.77). Ten participants had no prior experience with VR, ten participants reported using VR briefly at a demo or a friend's house, six reported using it a couple of times at a friend's house, one used it as part of another user study and one reported using VR as part of their job.

VI. Results

The results of the study are reported as follows: 1) Productivity; 2) Sense of Presence; 3) BANS' Usability; (4) Subjective BANS Perception; 5) Dismissed Notifications; 6) Rankings; and 7) Semi-structured Interviews. Data has been analysed using the non-parametric Friedman test due to not being normally distributed or based on non-parametric data collection (e.g., 7-point Likert scales). The Nemenyi test was used for post-hoc analysis, accounting for family-wise errors and is considered a conservative test [57, 69]. For all analyses, the *scipy.stats Python library*[4] was used. The results are discussed in Section VII.

A. Task Completion Time

Task completion times were compared across the productivity tasks to learn more about how the BANS impacted the participants' task completion times. Participants completed all seven productivity tasks with the *Baseline* in M = 82.86 s (SD = 48.02), *Text UI* in M = 93.71 s (SD = 59.67), *Avatar* in M = 94.57 s (SD = 50.63), *2D-Radar* in M = 93.0 s (SD = 59.53), *Attention Marker* in M=88.46 s (SD = 41.99), *3D-Scan* in M = 98.50 s (SD = 89.20) and *Passthrough* in M = 84.25 s (SD = 43.19). A Friedman test did not reveal any evidence of significant differences of task completion times when using the different BANS, $(\chi^2(6) = 0.62, p = 0.996)$. This means that there is no evidence that one of the BANS negatively impacted participants' task completion time compared to the other BANS. There is also no evidence that HMDs equipped with BANS impact VR users' task completion time in comparison to a VR experience without any bystander awareness notification (baseline).

B. Sense of Presence (IPQ)

We considered the four subscales of the IPQ [78], namely spatial presence, involvement, realism and general presence. *Attention Marker* scored highest in terms of spatial presence (SP), followed by the *Avatar*, *Baseline*, *2D-Radar*, *Passthrough*, *Text UI* and *3D-Scan*. A Friedman test on participants' reported spatial presence revealed no significant differences between the BANS, $(\chi^2(6) = 5.95, p = 0.43)$. For the involvement (INV) measure of the IPQ, *Attention Marker* scored highest, followed by the *Baseline*, *2D-Radar*, *Text UI*, *Avatar*, *3D-Scan* and *Passthrough*. There was evidence of a significant difference of involvement between the BANS, $(\chi^2(6) = 17.29, p = 0.008)$. Post-hoc Nemenyi tests revealed significant differences between *Passthrough* and *Attention Marker* $(p = 0.039)$ and between *Passthrough* and *Text UI* $(p = 0.039)$. For the realism (REAL) measure of the IPQ, *Attention Marker* scored highest, followed by the *Baseline*, *3D-Scan*, *2D-Radar*, *Text UI*, *Avatar* and *Passthrough*. There was no evidence of a significant difference between the BANS

[4]https://docs.scipy.org/doc/scipy/reference/stats.html

	(1) Baseline	(2) Text UI	(3) Avatar	(4) 2D-Radar	(5) Attention Marker	(6) 3D-Scan	(7) Passthrough	Friedman Test		Nemenyi *Post-hoc*
IPQ	**M (SD)**	**M (SD)**	**M (SD)**	**M (SD)**	**M (SD)**	**M (SD)**	**M (SD)**	$\chi^2(6)$	$p-value$	**Significant Pairs**
Spatial Presence	4.15 (1.14)	4.08 (1.21)	4.26 (1.24)	4.12 (1.20)	4.30 (1.19)	4.00 (1.30)	4.12 (1.22)	5.95	0.43	NA
Involvement	3.88 (1.25)	3.76 (1.20)	3.62 (1.18)	3.86 (1.21)	3.91 (1.20)	3.37 (1.39)	3.18 (1.29)	17.29	< 0.05	2-7, 5-7
Realism	3.37 (0.94)	3.27 (0.70)	3.14 (0.89)	3.29 (0.65)	3.46 (0.78)	3.29 (0.79)	3.09 (0.89)	4.53	0.61	NA
General Presence	4.46 (1.38)	4.00 (1.56)	4.43 (1.15)	4.07 (1.49)	4.36 (1.29)	4.25 (1.50)	4.36 (1.42)	4.07	0.67	NA
	M (SD)	**M (SD)**	**M (SD)**	**M (SD)**	**M (SD)**	**M (SD)**	**M (SD)**	$\chi^2(6)$	$p-value$	**Significant Pairs**
SUS	63.04 (31.26)	80.80 (15.38)	78.12 (17.82)	77.86 (17.61)	77.14 (18.73)	83.57 (17.82)	72.59 (25.32)	12.19	0.058	NA
7-point Likert Scale	**M (SD)**	**M (SD)**	**M (SD)**	**M (SD)**	**M (SD)**	**M (SD)**	**M (SD)**	$\chi^2(6)$	$p-value$	**Significant Pairs**
Noticeability	2.71 (2.19)	6.82 (0.47)	6.39 (1.45)	6.14 (1.33)	4.61 (2.13)	5.64 (2.09)	4.68 (2.79)	59.75	< 0.05	1-2, 1-3, 1-4, 1-6, 2-3, 2-5
Understandability	2.89 (2.18)	6.57 (1.08)	5.96 (1.72)	5.89 (1.37)	4.57 (2.11)	5.68 (1.96)	4.39 (2.54)	55.44	< 0.05	1-2, 1-3, 1-4, 1-6, 2-5, 2-7
Perceived Intrusiveness	1.89 (1.50)	3.61 (2.02)	2.93 (1.79)	3.29 (1.83)	1.89 (1.21)	2.75 (1.81)	3.00 (2.15)	26.97	< 0.05	1-2, 1-4, 1-5

TABLE I

MEANS AND SDS OF **IPQ**'S SUBSCALES (SPATIAL PRESENCE, INVOLVEMENT, REALISM, GENERAL PRESENCES, THE **SUS** SCORES AND THE **7-POINT LIKERT SCALE SCORES** (NOTICEABILITY, UNDERSTANDABILITY, PERCEIVED INTRUSIVENESS). GREEN DENOTES GREATEST MEAN, YELLOW SECOND GREATEST, AND ORANGE THIRD GREATEST. RED HIGHLIGHTS THE LOWEST MEAN. CELL HIGHLIGHTING IS INVERTED FOR *Perceived Intrusiveness* AS LOWER MEANS MEAN LESS INTRUSIVE. BLUE DENOTES $p < 0.005$

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as indicated by a Friedman test, $(\chi^2(6) = 4.53, p = 0.61)$. For the general presence (GP) measure of the IPQ, *Baseline* scored highest, followed by the *Avatar*, *Attention Marker*, *Passthrough*, *3D-Scan*, *2D-Radar* and *Text UI*. There was no evidence of a significant difference between the BANS in terms of participants' general presence, $(\chi^2(6) = 4.07, p = 0.67)$. Results are summarized in Table I.

C. BANS' Usability (SUS)

We analyzed the scores from the System Usability Scale (SUS [7]) using a Friedman test. There was no evidence of a significant difference of the BANS' SUS scores, $(\chi^2(6) = 12.19, p = 0.058)$. The 3D-Scan received the highest score M = 83.57 (SD = 17.82), followed by the *Text UI* M = 80.80 (SD = 15.38), *Avatar* M = 78.13 (SD = 18.15), *2D-Radar* M = 77.86 (SD = 17.93), *Attention Marker* M = 77.14 (SD = 19.07) and *Passthrough* M = 72.59 (SD = 25.79.15). The *Baseline* VR experience without any BAN system scored the least M = 63.04 (SD = 31.83). According to the adjective ratings scale by Bangor et al. [4], the usability of the BANS is considered to be between good (scored in the 70s) and excellent (scored in the 80s).

D. Subjective BANS Perception

After each productivity task, participants were provided with three questions aiming at evaluating the (1) Noticeability, (2) Understandability and (3) Perceived Intrusiveness of each BAN system on a 7-point Likert scale. Table I summarizes the means and standard deviations.

1) How easy or difficult was it to notice the notification? (Noticeability): A Friedman test revealed significant differences between the BANS in terms of their noticeability, $(\chi^2(6) = 59.75, p < 0.001)$. Post-hoc tests confirmed significant differences between *Attention Marker* and *Text UI* $(p = 0.005)$, between *Attention Marker* and *Avatar* $(p = 0.003)$, between *Baseline* and *3D-Scan* $(p = 0.001)$, between *Baseline* and *Text UI* $(p = 0.001)$, between *Baseline* and *Avatar* $(p = 0.001)$ and between *Baseline* and *2D-Radar* $(p = 0.001)$.

2) Once you noticed the notification, how easy or difficult was it to understand what it stands for? (Understandability): A Friedman test revealed significant differences between the BANS in terms of participants' understandability, $(\chi^2(6) = 55.44, p < 0.001)$. Post-hoc tests confirmed significant differences between *Attention Marker* and *Text UI* $(p = 0.005)$, between *Passthrough* and *Text UI* $(p = 0.003)$, between *Baseline* and *3D-Scan* $(p = 0.001)$, between *Baseline* and *Text UI* $(p = 0.001)$, between *Baseline* and *Avatar* $(p = 0.001)$ and between *Baseline* and *2D-Radar* $(p = 0.03)$.

3) How much of a hindrance was the notification to the overall VR experience? (Perceived Intrusiveness): A Friedman test revealed significant differences between the BANS in terms of participants' perceived intrusiveness, $(\chi^2(6) = 26.97, p < 0.001)$. Post-hoc tests confirmed significant differences between *Attention Marker* and *Text UI* $(p = 0.04)$, between *Baseline* and *Text UI* $(p = 0.018)$ and between *Baseline* and *2D-Radar* $(p = 0.03)$.

E. Dismissed BANS' Notifications

Participants could dismiss the notifications once triggered by the BANS, as described in Section III. The *Baseline* condition was excluded for this analysis as there was no notification to dismiss. *Text UI* was dismissed by 13 out of 28 participants. *Avatar*, *Attention Marker* and *Passthrough* were dismissed 15 times each. *2D-Radar* and *3D-Scan* were dismissed 18 times each. A Cochran's Q test revealed no significant effect of BAN system on participants' dismissal behavior $(\chi^2(5) = 3.72, p = 0.59)$.

F. Preference Ranking of the BANS

Participants were asked to rank the BANS in terms of usability, privacy and combined usability and privacy. For the analysis, a weighted rank (WR) was calculated for each condition based on the rankings of the participants (e.g., frequency rank 1 × 7 + frequency rank 2 × 6, etc.).

1) Perceived Usability: The rankings from most usable to least usable were: (1) *3D-Scan* (WR = 145), (2) *Text UI* (WR = 133), (3) *2D-Radar* (WR = 125), (4) *Passthrough* (WR = 123), (5) *Avatar* (WR = 118), (6) *Attention Marker* (WR = 108) and (7) *Baseline* (WR = 32). The *3D-Scan* was rated most usable or second most usable by 17 out of 28 participants. The *Text UI* and the *Passthrough* were rated most usable or second most usable eleven times.

2) Perceived Security: The rankings from most secure to least secure were: (1) *3D-Scan* (WR = 153), (2) *2D-Radar* (WR = 131), (3) *Text UI* (WR = 126), (4) *Passthrough* (WR = 123), (5) *Attention Marker* (WR = 114), (6) *Avatar* (WR = 109) and (7) *Baseline* (WR = 28). The *3D-Scan* was rated most secure or second most secure by 16 out of 28 participants. The *2D-Radar* was rated most secure or second most secure nine times. The *Text UI* was rated most secure or second most secure eight times. Due to the absence of any notification, participants rated the *Baseline* as least secure.

3) Combined Perceived Usability and Security: The rankings from most usable and secure to least usable and secure were: (1) *3D-Scan* (WR = 149), (2) *2D-Radar* (WR = 138), (3) *Text UI* (WR = 126), (4) *Passthrough* (WR = 118), (5) *Attention Marker* (WR = 114), (6) *Avatar* (WR = 111) and (7) *Baseline* (WR = 28). *3D-Scan* was rated most usable and secure or second most usable and secure by 15 out of 28 participants. *2D-Radar* was rated most usable and secure or second most usable and secure eleven times. *Text UI* was rated most usable and secure or usable and most secure eight times. All participants rated *Baseline* as least usable and least secure.

G. Semi-structured Interviews

We concluded with semi-structured interviews to learn more about participants' experiences and opinions when using the different BANS. This allowed us to better understand how the BANS' different information granularity levels contribute to participants' sense of privacy. The data was first transcribed and then split into meaningful excerpts. All participant statements (n=234) were then systematically clustered by the lead researcher using an affinity diagram on Miro. The clusters were reviewed by a second researcher, who added tags and iterated over the initial themes. This process resulted in three main themes:

1) ***BANS' Information Displayed and Its Extraction****:* Participants' opinions varied when they were asked about their opinions on the amount of information each BAN system displayed. 14 participants found it sufficient getting notified about an observation, while the other half felt the urge to receive more details about the observation. Most participants mentioned that *Text UI* was *"disturbing"* and *"confusing"* because it delivers a feeling of urgency but not enough information to build VR users' awareness: *"this sign that popped up shortly showing "someone was watching you". I thought at first that might be good but then I didn't know what to make with that information, because I didn't know who was watching and what that person has been doing and for how long he or she was watching me"* (P16). However, participants voiced that displaying more information did not necessarily help them to identify the observer. The way the information was presented was considered to play a bigger role. For example, both *Avatar* and *2D-Radar* displayed the location of the bystander. However, only three participants reported being able to interpret the position of the bystander using *Avatar* in comparison to 12 using *2D-Radar*.

Participants' responses along with the BANS' information displayed shed light on how important the extraction of information from VR users' surroundings is and how different forms of presentation affect user perception. Although *Passthrough* showed the real-world surrounding of the VR user, 21 out of 28 participants voiced that they were not able to identify the bystander: *"And for the other ones [BANS], what I found useful is that you can see where the intruder is, or sometimes who the intruder is... I think that's why I don't like this one [Passthrough], because it doesn't have either of that, you just see the train. And if he's behind you, then it is not very prominent and you also don't see who exactly is the intruder because you see everybody."* (P07). In contrast, *3D-Scan* extracted the information the VR users need from the reality and displayed it as is, which made it easier for most participants to get notified, then identify the bystander and not feel the urge to remove the headset to "search" for the bystander: *"[3D-Scan] gives awareness that somebody's actually there because you saw the direct image of the person who was looking at you... I could localize him better and also have a better feedback to the train reality."* (P13).

2) ***BANS' Configurability****:* Participants reported that they would find it useful to be able to freely configure the behavior of the BANS. In particular, there was a general consensus that the duration of a bystander awareness notification and how it can be dismissed should consider contextual factors. For example, participants reported that on one hand, if they are using the HMD for entertainment, bystander awareness notifications should be either short or not displayed at all. On the other hand, if they are using it in a more critical context (e.g., authentication or entering sensitive information), they would prefer that the bystander awareness notification would be more prominent and persistent: *"If I'm gaming or something, then I don't want something to pop up because what do I care if somebody's watching me play Minecraft or whatever. Because then I think it would just be distracting from the game or from the book I read or whatever. So if I don't care, I can just switch it off."* (P07). P13 voiced that they *"think this should be configurable in any case, because as a private person, I might not have so many concerns about the data, but as an employee, I might have specific rules and they have to be kept."* (P13).

3) ***BANS' Usability****:* The interviews shed light on how participants assessed the BANS' usability. They had different opinions on the notifications' intrusiveness. Some perceived the high intrusiveness of a notification (e.g., *Text UI*) as important for the preservation of their privacy as it instantly grabs their attention, provides them the urge to act, and decreases chances of missing it: *"These more, what's the word I guess, invasive ones, where you see them in front of your eyes. And I like that [...] I guess the point of these notifications is to get you to notice if there is an attacker or someone looking over your shoulder. And therefore, since [the VR headset] is quite immersive, I guess it would be good for the system to be very upfront..."* (P20). However, other participants found such a high level of intrusion disturbing and voiced that it breaks their immersion and overall VR experience: *"It's Attention Marker kind of better because it's less invasive. But that's kind of also the problem."* (P15). The problem that participants mentioned about BANS that are less intrusive is that it is easier for them to miss it, which, according to some participants, then makes more unobtrusive BANS not reliable. As for the understandability of the BANS, participants found *Passthrough* the hardest system to understand due to the transition from virtuality to reality. Some participants were confused and did not properly understand why they now see the train environment (i.e., their real-world surrounding). In contrast to *Passthrough*, participants found *Text UI* easy to understand because of the simplicity of its design, communicating to VR users that they are being observed from reality without providing additional contextual information.

VII. Discussion

We evaluated different BANS to support VR users' in preserving their privacy in public. Results show that BANS provide participants with a reasonably higher sense of privacy than HMDs without BANS (baseline in this work). Furthermore, there is no evidence that the use of BANS negatively affects VR users' experiences (Section VI-A).

3D-Scan outperformed the other conditions in terms of usability, privacy and combined usability and privacy. Participants stated the benefits of *3D-Scan* over the other BANS were mainly because *3D-Scan* provided sufficient information about their surrounding reality to assess the situation without being too intrusive compared to the other BANS (e.g., *Passthrough*: *"You get thrown out of the whole VR experience" (P03)*). One participant voiced that in *3D-Scan*: *"[they] really kind of have the feeling of where the person is, more real, not only where [the observer] is located but [the observer's] figure [...] it makes [them] more conscious about the person."* (P12). *Attention Marker*, meanwhile, delivered a greater feeling of spacial presence, a higher sense of involvement and a higher experienced realism than the other BANS, highlighting *Attention Marker's* subtleness and high integration in the virtual environment. However, BAN systems that are unobtrusive are at risk of not efficiently supporting VR users' privacy. For example, *Attention Marker* was ranked as "the most notifications missed" by participants (Section VI-G).

In the following, we discuss the importance of 1) balancing bystander privacy with VR users' bystander awareness, 2) balancing noticeability with intrusiveness and 3) the relevance of contextual factors when designing VR HMDs equipped with BANS. We conclude with four recommendations for the design of future privacy-preserving VR HMDs equipped with BANS.

A. Balancing VR Users' Bystander Awareness & Privacy

Participants voiced they felt their privacy was most preserved by VR HMDs equipped with *3D-Scan* and *2D-Radar*. This suggests VR users tend to feel more secure when more identifiable information about bystanders is conveyed compared to only notifying VR users about an observation without any contextual information. For example, in comparison to *Text UI*, which only informs the VR user someone is observing them, *3D-Scan* provides additional contextual information, including the observer's identity and location in the real world. While this facilitates protecting the VR users' privacy, it may be considered a violation of the bystanders' own privacy due to the VR HMDs' continuous sensing of the real environment.

Capturing real-world information might not be sensitive to the VR user themself, but to other entities in users' proximity, to which De Guzman et al. [10] refer as "bystander privacy". Some have made recommendations to "communicate to users when their data is being collected in real time" [1] while others have argued "most interactions involve VR users and bystanders that know each other" [67]. However, in more complex scenarios, such as using HMDs for productivity on a train, there is a fundamental change in the relationship between VR users and bystanders (who are most likely strangers). This raises important questions: Are non-familiar bystanders considered co-users as they are part of the VR users' experience due to the HMDs' "always-on" real-world sensing?

If it is of importance to communicate to VR users when data is being collected, it seems equally important to communicate the same information to bystanders. There are many ways in which a bystander's information can be misused [60, 63, 67] and yet there is no opportunity for bystanders to opt out from BANS that sense their presence, highlighting the need for designing, implementing and evaluating BANS that put bystanders' privacy into consideration. For example, what if VR HMDs equipped with BANS incorporate bystanders into the VR users' virtual experience (e.g., *3D-Scan*) without the bystanders' consent? While VR users have a right to be aware of who is in their vicinity due to safety and privacy concerns [17, 29, 60, 67] and because of bystanders' position of power over VR users who lack reality awareness [67], the same right should be given to bystanders and their privacy. Acknowledging that prioritizing VR users or bystanders desire alone serves only to harm the other, future work is required to design BANS that provide VR users with enough information about bystanders to facilitate their privacy protection whilst respecting bystanders' privacy.

B. The Fine *Line Between Noticeability and Intrusiveness*

Results show that *Text UI* received a high noticeability and understandability score relative to the other BANS. Participants described *Text UI* as "*eye catching*" and "*very prominent*". However, this level of noticeability resulted in it being "*disturbing*" to the overall VR experience as described by participants. Contrary to *Text UI*, the results of the *Attention Marker* indicate it was the least intrusive and the least noticeable across all BANS, excluding the baseline. This observation is in line with previous work. Both Rzayev et al. [74] and Ghosh et al. [24] found that participants perceive more noticeable notifications as significantly more intrusive than those less noticeable. Rzayev et al.'s [74] results indicate egocentric notifications are significantly more noticeable and intrusive than those placed in world space, resulting in a significant effect of notification placement on the chance of users missing the notification. A similar effect was observed among the BANS evaluated in this work, for example, the number of dismissed BANS' notifications in *Attention Marker*, indicating a negative correlation may exist between the BANS' noticeability and intrusiveness. Future research should therefore follow up this result and explore the interplay between peripheral input devices for VR, BANS, noticeability, and intrusiveness in more depth.

C. Variety of (Public) Contexts and its Impact on BANS

Research investigating BANS has so far exclusively been conducted in the lab [24, 25, 35, 49, 59, 62]. In-the-wild investigations are increasingly important as VR HMDs are expected to find widespread adoption in more vivid public environments in the near future. Even though participants found *3D-Scan* the most usable BAN system relative to the others, some participants thought *3D-Scan* would be distracting with multiple observers. Accidental observations, for example, a quick glance from a passenger on a train to the right, might not be uncommon. In such scenarios, BANS must be able to distinguish between observations targeting the VR user and observations as part of social interactions. *Passthrough*, for instance, is one example of a BAN system that might not be appropriate for use in public spaces. Participants often referred to it as "distracting and confusing", that they were seeing everyone around them, that they *"couldn't concentrate"* and that it increased their mental workload. Contrary to our findings, prior work highlighted *Passthrough*'s performance in confined to private spaces where bystanders are rare and, if collocated to the VR user, mostly known by the VR user [25, 35, 59]. The differences between VR users' preferences of BANS in private, semi-public and public spaces highlight the need of contextual BANS to adjust their level of reality awareness delivered to the VR user depending on the context. Exposing participants multiple times to the same BANS might have an effect on VR users' perception of these systems and their productivity, highlighting the need for future research that assesses BANS in various real-world contexts and VR experiences.

D. Lessons Learned

1) First Lesson Learned: Transitioning VR users between realities can be disturbing and can negatively impact their overall VR experience, requiring a need to assist VR users when transitioning between realities (e.g., from a virtual workspace to their real-world surroundings). Although *Passthrough* displayed the most amount of information from the VR users' reality, participants found it *"complicated"* and *"noisy"*. 21 out of 28 participants were not able to identify the observer in *Passthrough* because participants had to process all the information they were perceiving without any additional assistance from the BAN system, resulting in an information overload: *"[...] the 3D-Scan is a better version of the Passthrough, because the Passthrough doesn't assist you in locating the attacker, but the 3D Scan tells you their location exactly"* (P02). A rapid change of VR (i.e., virtual workspace) to reality (i.e., real-world train environment) might even be more misleading in vivid environments where the reality, when the VR user entered virtuality, is not in line anymore with the "new" reality during or after the VR experience. For example, some passengers get off earlier than the VR user while others, i.e., new passengers, might get on the train. VR users who are fully immersed in VR productivity tasks might not notice these changes in their reality until a BAN transitions them from VR back to reality due to an observation. This suggests extracting information from the VR users' reality, providing seamless transitions between realities [23, 27, 59] and aiding them when transitioning between two different realities is necessary to positively contribute towards VR experiences while keeping the additional workload introduced by a transition along the Reality-Virtuality continuum [55] as low as possible.

Recommendation 1

Consider how VR users can best be transitioned between realities when their bystander reality awareness is of relevance due to privacy or safety reasons. An instant switch from virtuality to reality (e.g., Passthrough) might be confusing as the VR users' previous knowledge about reality might no longer hold true due to changes in the real world (e.g., additional/different bystanders).

2) Second Lesson Learned: The use of BANS has shown great potential in aiding VR users in maintaining awareness of their real-world surroundings without negatively affecting their sense of presence and VR experience. Participants voiced feeling safer with BANS compared to state-of-the-art VR HMDs without any BAN system (baseline), for example, P27 mentioning they *"felt very vulnerable"* during the baseline condition. Not being aware of one's real-world surroundings while entering privacy-sensitive information may also lead to anxiousness as expressed by one participant *"it was like, oh my god, what's happening?"* (P19), indicating that BANS should be designed in a way to support VR users' bystander reality awareness. However, as discussed in Section VII-A the additional privacy protection of VR users should not come in exchange of bystander privacy. Therefore, it remains an ongoing challenge to design, develop, and evaluate BANS to support VR users in maintaining their privacy whilst not invading nearby people's privacy.

Recommendation 2

HMDs equipped with BANS should be designed and implemented to support VR users in preserving their privacy, but it is equally important to maintain nearby people's privacy.

3) Third Lesson Learned: The use of different modalities to notify VR users, for example, visual and auditory feedback, increases the probability notifications are seen by the user [24]. The qualitative results in Section VI-G indicate that some participants missed notifications from *Attention Marker* on the peripheral device because of its positioning in world space and participants' typing behavior (i.e., touch typing without paying attention on the keyboard [16]). However, participants mentioned they still were aware: *"I knew that I was being watched because I heard the tone"* (P14). One participant mentioned that *"If I don't look at the keyboard then I don't see it. Actually I recognized it a couple of seconds later"* (P03). These findings are in line with previous work who have argued a combination of different modalities (e.g., visual, aural and haptic feedback) are beneficial for attracting a VR users attention [24, 53]. Therefore, building upon the previous comments on supporting users when transitioning between realities (Recommendation 1), it is important to support users in noticing notifications that might be out of their view.

Recommendation 3

Visual notifications that are not in VR users' peripheral vision, e.g., Attention Marker in combination with peripheral input devices, can be easily missed. Therefore, we recommend to implement different modalities, such as combining visual with auditory feedback, or to support VR users in noticing out-of-view notifications to inform them about privacy-critical observations from reality.

4) Fourth Lesson Learned: VR users' lack of control over how the BANS are triggered or dismissed can cause *"frustration"*, as described by one of our participants. Out of 28 participants, 22 mentioned the need of having the control over dismissing the notifications (e.g., by continuing providing input on a peripheral device like a keyboard). If VR HMDs find widespread adoption for public use, they will likely find application in different domains, including entertainment and productivity. The variety of contexts requires BANS to adjust their behavior and align with VR users' preferences. For example, in semi-public scenarios (e.g., in a shared real-world office environment) a person immersed in a productivity task in VR might not feel the need to enable BANS. Similar to the "no one size fits all" comments on notifications in VR [53, 62] which discuss the need for a VR HMD to support multiple BANS and allow users to tailor them to their personal preferences, VR users are ideally in full control of BANS and can decide when and how they want to "dismiss", "snooze for N minutes", or "disable" the notifications.

Recommendation 4

VR users should be provided with full control over BANS and their functionality. There is no "one size fits all" BAN system for the breadth of VR experiences. VR users should have a choice of when and how BANS notify them about privacy-critical observations.

VIII. Limitations

There are some limitations that are worth discussing. First, we applied a "nested reality" [84] research approach to depict reality and virtuality in VR. While simulating reality in VR is a common approach within the HCI and VR communities (e.g., [27, 45, 47, 54, 58]), it is important to acknowledge potential differences to in-the-wild studies of the BANS. However, to evaluate, for the first time, the BANS' usability and participants' perception of their effectiveness in VR productivity tasks it was important to be in full control of VR and reality. Our results from the lab study will guide the community in designing privacy-preserving VR HMDs and will inform follow-up studies in real travel scenarios once practical and feasible. Second, we studied BANS in combination with a physical keyboard. Keyboards are frequently used for text manipulations and productivity tasks in physical office environments and the VR community and the industry put in significant effort into blending (physical) keyboards into VR (e.g., [31, 49, 86] and Oculus' Tracked Keyboard SDK [11]). Future work is required to study the breadth of BANS when using different peripheral devices, including mice, multi-surface VR pens [73], VR controllers, and more.

Finally, we assumed future HMDs equipped with BANS to be capable of accurately sensing the real environment and informing VR users about potential bystander observations. While this contributes towards the protection of the VR users' privacy, it invades the (passive) bystanders' privacy due to the HMD's continuous sensing of the real environment. Future work is required to design and implement BANS that provide a right balance of protecting VR users' and bystanders' privacy, including "passive" bystanders who may be part of the VR user's real-world surroundings but do not interact and/or observe them.

IX. Conclusion

This paper investigated the use of Bystander Awareness Notification Systems (BANS) for enhancing VR users' bystander awareness during productivity tasks in VR. We showed how BANS increase VR users' bystander awareness without affecting their presence and VR experience. VR users prefer BANS that extract and present them with a considerable amount of reality information. The results show that assisting VR users in extracting information about bystanders from the reality is necessary to reduce confusion and disruption. Through our investigation of using BANS to help preserve VR users' privacy in public spaces, we contribute to a future of privacy-preserving HMDs. Future research is encouraged to investigate methods that further improve bystander awareness systems and contribute towards a future where privacy-preserving HMDs find widespread adoption and result in more enjoyable, secure and productive travels.

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Appendix

A. *Questionnaires*

Noticeability, Understandability and Preceived Intrusiveness (7-point Likert scale questions)

1) How easy or difficult was it to notice the notification?
2) Once you noticed the notification, how easy or difficult was it to understand what it stands for?
3) How much of a hindrance was the notification to the overall VR experience?

iGroup presence questionnaire (IPQ) [78]

1) How aware were you of the real world surrounding while navigating in the virtual world? (i.e., sounds, room temperature, other people, etc.)?
2) How real did the virtual world seem to you?
3) I had a sense of acting in the virtual space, rather than operating something from outside.
4) How much did your experience in the virtual environment seem consistent with your real world experience ?
5) How real did the virtual world seem to you?
6) I did not feel present in the virtual space.
7) I was not aware of my real environment.
8) In the computer generated world I had a sense of "being there"
9) Somehow I felt that the virtual world surrounded me.
10) I felt present in the virtual space.
11) I still paid attention to the real environment.
12) The virtual world seemed more realistic than the real world.
13) I felt like I was just perceiving pictures.
14) I was completely captivated by the virtual world.

System Usability Scale (SUS) [7]

1) I think that I would like to use this system frequently
2) I found the system unnecessarily complex
3) I thought the system was easy to use
4) I think that I would need the support of a technical person to be able to use this system
5) I found the various functions in this system were well integrated
6) I thought there was too much inconsistency in this system
7) I would imagine that most people would learn to use this system very quickly
8) I found the system very cumbersome to use
9) I felt very confident using the system
10) I needed to learn a lot of things before I could get going with this system

B. *Semi-Structured Interview Questions*

1) Please order the notification systems by preference in terms of usability.
2) Please order the notification systems by preference in terms of security.
3) Please order the notification systems by preference in terms of both usability and security.
4) What aspects of the notifications were useful and problematic?
5) How long (or often) should the notifications be displayed and what are strategies for their removal?
6) Was it enough to know that you're being observed or do did you feel the urge to know who?
7) For some notification methods, would you have preferred that they were on throughout the whole task?
8) Was it easy to identify the bystander who was observing you?
9) Was it easy to stay aware of bystanders?
10) Did you have the urge to remove the headset?

C. *Productivity Tasks in Virtual Reality*

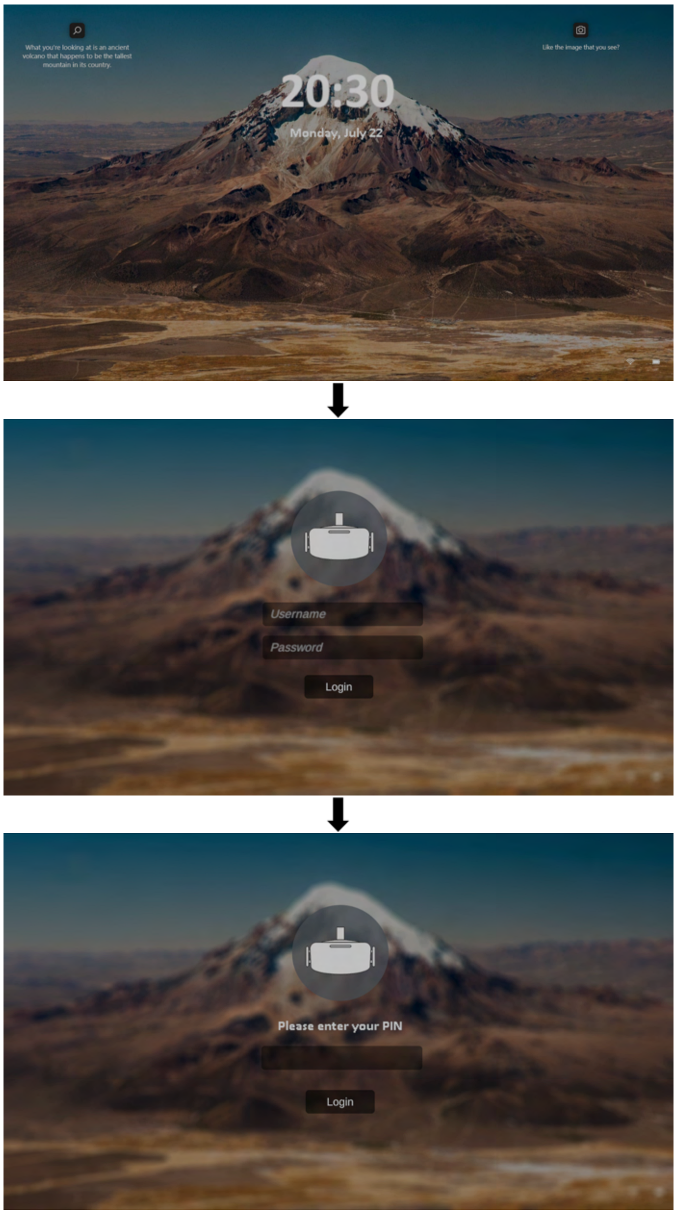

Fig. 4. Task #1: Windows Login

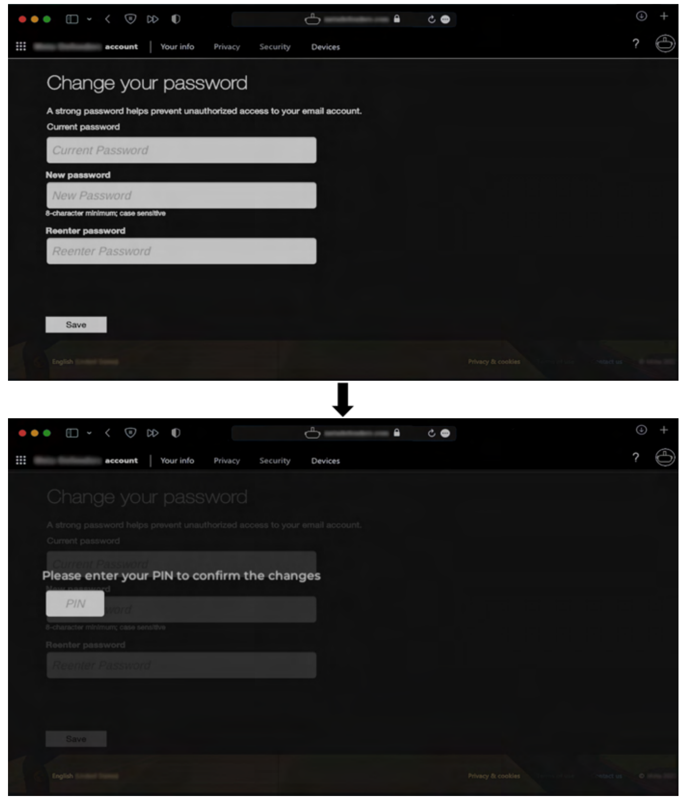

Fig. 5. Task #2: Change Email Password

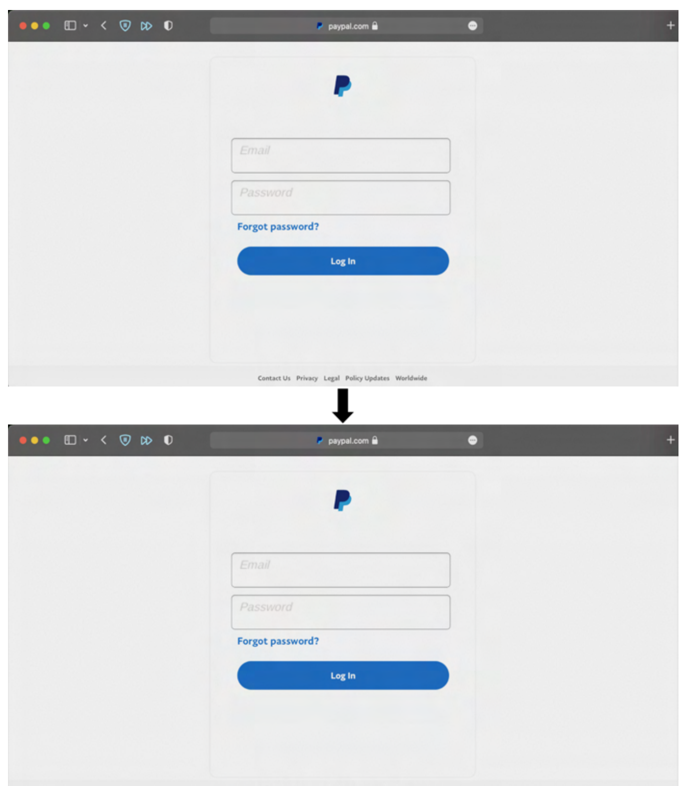

Fig. 6. Task #4: Login to Paypal

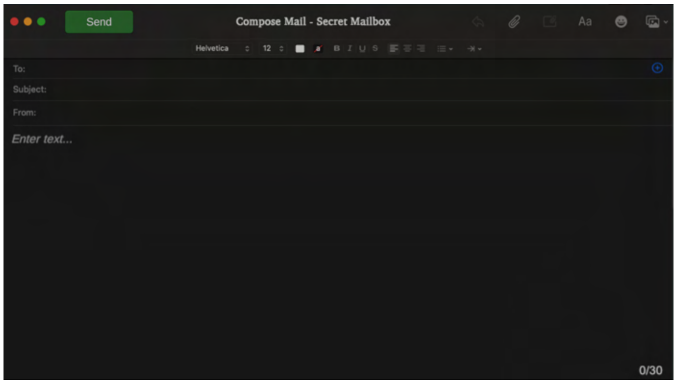

Fig. 7. Task #3: Send an Email

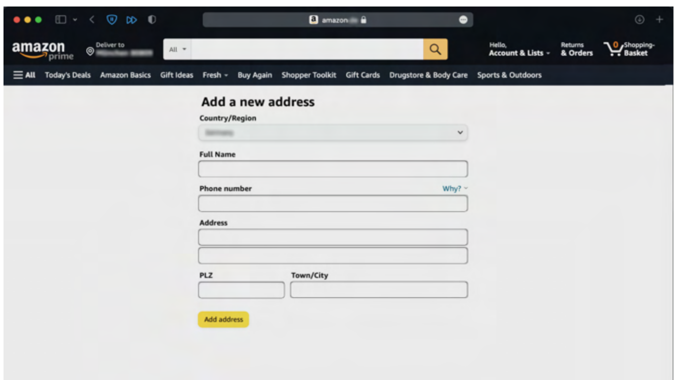

Fig. 8. Task #5: Add Address to Amazon

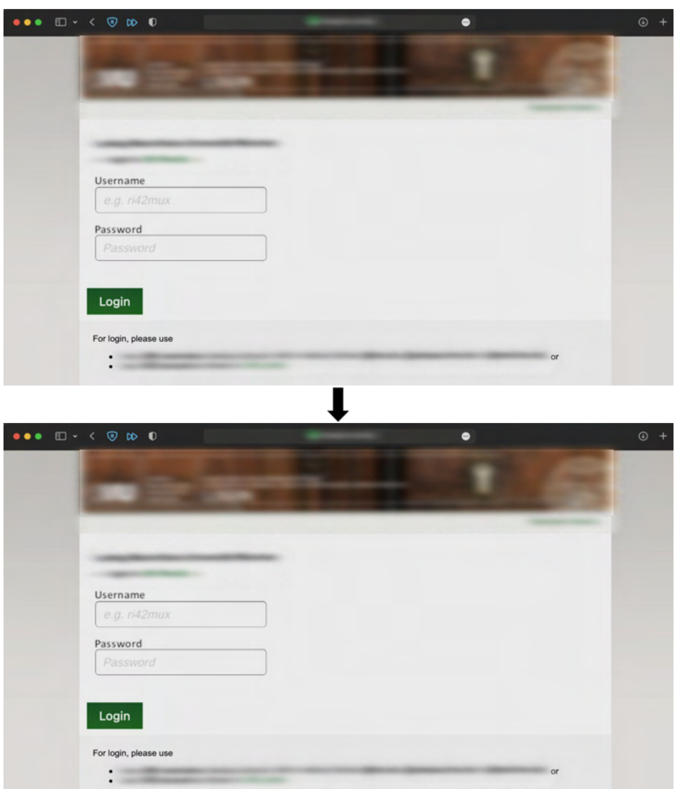

Fig. 9. Task #6: Login to University Portal

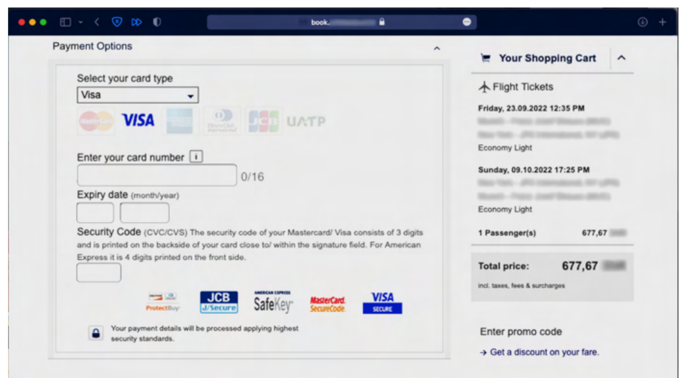

Fig. 10. Task #7: Book a Flight