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Investigating guardian awareness techniques to promote safety in virtual reality

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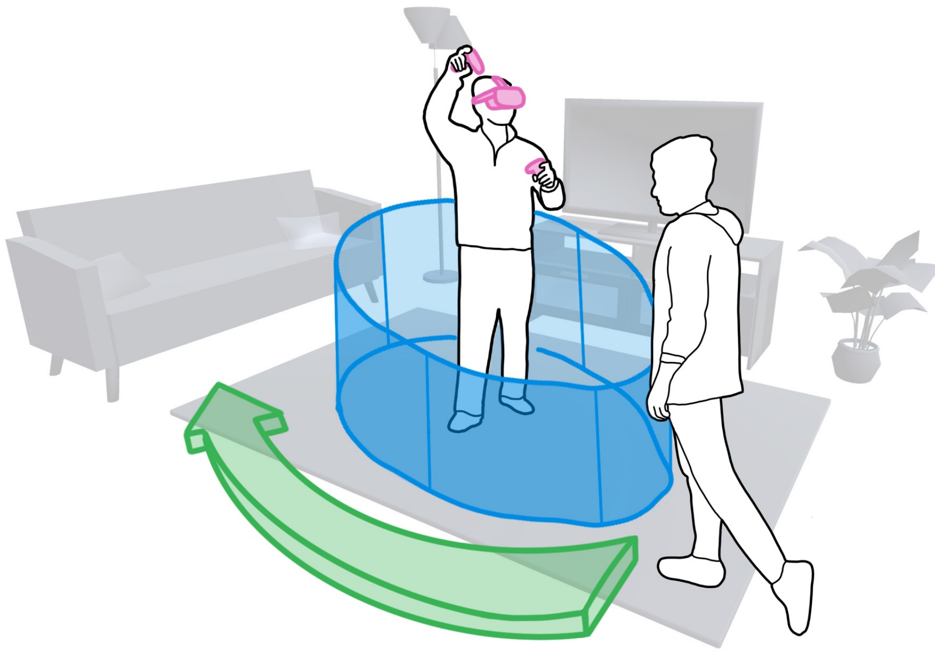

Figure 1: Our research aims to address the problem: how to help a bystander to safely circumvent the invisible guardian around the Virtual Reality user with devices that the bystander already carries.

Abstract

Virtual Reality (VR) can completely immerse users in a virtual world and provide little awareness of bystanders in the surrounding physical environment. Current technologies use predefined guardian area visualizations to set safety boundaries for VR interactions. However, bystanders cannot perceive these boundaries and may collide with VR users if they accidentally enter guardian areas. In this paper, we investigate four awareness techniques on mobile phones and smartwatches to help bystanders avoid invading guardian areas. These techniques include augmented reality boundary overlays and visual, auditory, and haptic alerts indicating bystanders' distance from guardians. Our findings suggest that the proposed techniques effectively keep participants clear of the safety boundaries. More specifically, using augmented reality overlays, participants could avoid guardians with less time, and haptic alerts caused less distraction.

Index Terms: Human-centered computing—Visualization—Visualization techniques—Treemaps; Human-centered computing—Visualization—Visualization design and evaluation methods

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1 Introduction

With the increasing popularity of Virtual Reality (VR) in daily life, there has been growing discussion on the safety of VR device usage in everyday environments shared by VR users and bystanders. Head-Mounted Displays (HMD) immerse the wearer in virtual worlds [24] and isolate users from the surrounding physical environments. Consumer VR systems provide guardians—pre-defined boundaries around users—to reduce collisions between HMD users and the surrounding environments by raising alerts when users reach or step out of the boundaries. However, guardians are typically only visible to HMD users not bystanders, who may accidentally break guardians and collide with VR users [7]. A common approach to avoid collisions is to visualize the presence of bystanders to VR users [24, 31, 44] as alerts. However, this approach introduces "artifacts" to virtual worlds and may break the sense of immersion for VR users.

Instead of pulling VR users out of the virtual world to react to possible collisions, we explore lightweight techniques that guide *bystanders* to actively circumvent guardians to improve the safety of VR usage.We designed and evaluated four novel guardian awareness techniques to safely and efficiently guide bystanders around guardians through guardian awareness techniques on phones and smartwatches (Fig. 1). We further note that bystanders often need to navigate around VR users while engaged in other activities such as texting on phones or finding directions at the same time. Thus,

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the awareness techniques should minimize distraction to bystanders' ongoing activities.

Drawing on prior work in navigation cues on mobile devices [14], we propose four techniques for helping a bystander to navigate around the guardian of a single collocated VR user. *Augmented Reality* provides global awareness about guardians by visualizing guardian boundaries through video augmented reality on bystanders' phones. *Visual Alert*, *Haptic Alert*, and *Auditory Alert* use color, vibration, and sound, respectively, to notify bystanders of their distances to guardian boundaries. Through controlled studies where participants circumvented around VR guardians assisted by one of the techniques or no technique at all, we evaluated our proposed guardian awareness techniques in terms of safety and efficiency. To understand the distraction that guardian awareness techniques may cause on bystanders, we further studied the safety and efficiency of these techniques when their users were texting on phones, and compared how individual techniques affect text-input performance.

We found that all techniques were effective in reducing invasion into guardians. Participants took the least amount of time reaching their destinations with *Augmented Reality*. However, *Haptic Alert* introduced the least amount of distraction when participants needed to split their attention between locating guardians and typing. Overall, our results show the efficacy of guardian awareness techniques in making VR usage collocated with other people safer. The trade-off between efficiency and distraction suggests adaptively choosing awareness techniques based on bystanders' current engagement level with their phones.

2 Related Work

This section includes relevant research in (1) Pedestrian safety systems, (2) HMD non-HMD interaction and context awareness of HMD users, (3) Safety boundaries in virtual reality.

2.1 Pedestrian safety systems

Our work is aiming at helping bystanders to avoid collisions with HMD users and walk to their destination while the bystander and the HMD user share the same physical space. Lack of context information while walking can cause collision with obstacles [1,32]. CrashAlert [14] utilized a depth camera to detect potential obstacles on users' paths and displayed visual cues on users' smartphones. Lookup [21] leveraged a shoe-mounted motion sensor to detect the transition of walking from the sidewalk to the road. WalkSafe [47] used a phone camera to detect front and back views of moving vehicles. It also alerted users via vibration and sound in unsafe conditions. Kang et al. [22] designed a system for smartphone AR users to avoid collision by extracting feature points from camera input.

Much prior research work in pedestrian safety systems focused on the improvement of the obstacle detection algorithm.This was because obstacles in the pedestrian safety contexts are visible. Kiefer et al. [23], Kang et al. [22], Braun et al. [2], Straughn et al. [40] discussed the effectiveness of alerting system in different modalities. The alerting systems can be considered effective as long as they can make users aware of the existence of obstacles, then users can look away from smartphones and circumvent the obstacles. On the other hand, the guardians of VR users are invisible, and bystanders have to keep using our techniques to understanding their relative positions to VR guardians.

2.2 HMD non-HMD interaction and context awareness of HMD users

Prior works focus on interaction designs between HMD users and non-HMD users. Non-HMD users can learn the experience that HMD users have through projection, mobile devices, etc. ShareVR [11] utilized floor project and mobile displays to allow non-HMD users to have asymmetric interaction experiences with HMD users. Similarly, MagicTorch [26] explored asymmetric interaction techniques for HMD users through projection and tablet. This technique allows co-located HMD users and non-HMD users to play the same VR game at the same time. Dollhouse [20] developed by Ibayashi et al. proposed a solution to collaboration on room design. The system supports HMD users to have a first-person immersive view while non-HMD users design the room via a bird-view perspective simultaneously. Furthermore, Gegenheimer et al. proposed FaceDisplay [12], integrated with touch-sensible displays and depth cameras. The hardware supports interactions of non-HMD users with HMD users through touch and gesture. In addition, FrontFace [5] proposed by Chan et al., leverages an eye-tracker integrated into HMD to display the facial expression of HMD users to non-HMD users. Moreover, Mai et al. introduced TransparentHMD [28] and applied head-coupled perspective techniques to produce the illusion of transparent HMD. Grandi et al. [10] evaluated the easiness and mental workload of collaboration tasks through VR-VR interaction, AR-AR interaction, and VR-AR interaction. They concluded AR-VR interaction outperformed AR-AR and reaches similar results as VR-VR interaction. Similar to our project, the goal of our project is to display the guardians of VR users to non-HMD users. However, interaction skills design is the key point of current related works. The novel point of our work is exploring and evaluating guardian awareness techniques that can help bystanders' acquire information of guardians that exists in VR environments but not in physical environments.

Context awareness of HMD users is important. Among all VR fails, 10% [7] of them are caused by hitting. NotifiVR [9] designed techniques to notify HMD users when the environment changes. They prototyped 5 notifications and conducted a user study across 6 different modalities. Rzayev et al. [36] explored the impact of notification appearance positions on both effectiveness and comfort. They tested the designed notification techniques among different tasks and environments that HMD users work in. Tao and Lopes [42] used sensors to detect real-world environmental changes and adapt the virtual environment accordingly, which reduces distraction to VR users. Previous research works [24, 33, 44] also explored methods to notify HMD users of bystanders' presence. Hagan and Williamson [33] implemented bystander presence notification in multi-modalities including text, avatar, audio, and radar. Kudo et al. [24] and Willich et al. [44] focus on the design on vision. Kudo et al. implemented techniques visualizing bystanders' position and orientation to HMD users while Willich et al. developed methods to simulate bystanders through Augmented Virtuality. Previous works notified HMD users of co-located bystanders' presence. In this way, sense of immersion can be broken and HMD users need extra mental effort to notice the presence of bystanders [3,29]. We explored the methods that can notify bystanders of VR users' guardians to keep safe.

2.3 Safety boundaries in Virtual Reality

Safety is an active research area in virtual reality [34]. Safety boundaries are useful to keep HMD users safe in the physical world when they are immersed in the virtual environment. Previous research explored the methods to notify HMD users of safety boundaries based on distance and velocity [51]. In addition, redirect walking can be utilized to provide dynamic safety boundaries for HMD users [6,16,17]. Furthermore, Sra and Marwicke et al. [30,39] extend the concept to avoid collision of multiple local HMD users collision by using the redirected walking technique. Camera and depth sensors are used to detect obstacles in previous research works [4,8,52]. Moreover, it is extended to be used to project objects in the physical environment to the virtual reality environment [18,19,41,48]. RealityLens [45] enables VR users to peep into the physical world using a portal widget. Yang et al. proposed DreamWalker [49] leveraging sensor fusion for HMD users to observe position, obstacles, and bystanders

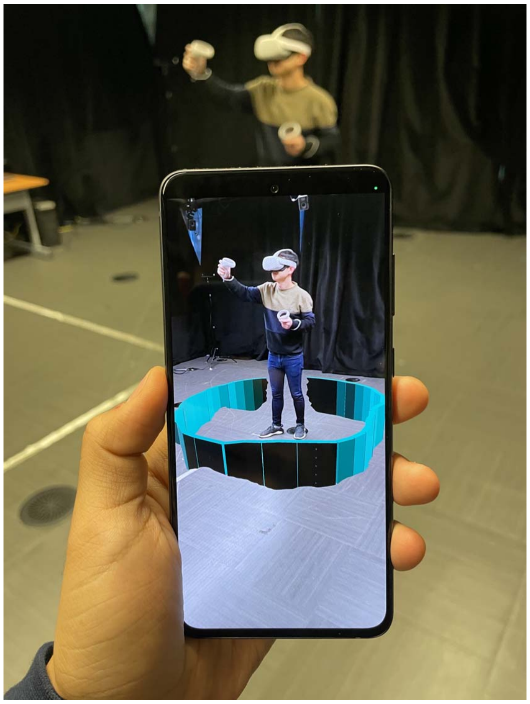

Figure 2: The *Augmented Reality* technique displays the guardian in-situ as a turquoise-color, three-dimensional barrier.

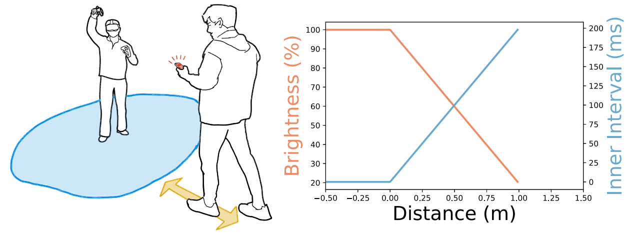

Figure 3: *Left: Visual Alert* use a flickering bar to notify the bystander of their distance to the guardian. *Right:* The brightness of the bar increases and the interval between its two consecutive appearances decreases as the bystander gets closer to the guardian. The value of the brightness axis indicates the percentage of the maximum color brightness of the notification bar.

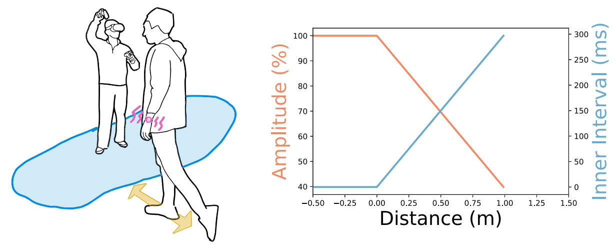

Figure 4: *Left: Haptic Alert* use vibration to notify the bystander of their distance to the guardian. *Right:* The amplitude of the vibration pulses increases and the interval between two consecutive pulses decreases as the bystander gets closer to the guardian. The value of the amplitude axis indicates the percentage of the maximum vibration amplitude of the device.

in the physical world. ShareSpace [50] provided a safety boundary for co-located HMD users and non-HMD users to support communication on shared space usage. Previous related works focus on HMD users' collision avoidance of the physical environment by providing dynamic safety boundaries. Displaying cues of physical objects and redirected walking can be considered dynamic safety boundaries since those techniques ensure HMD users' safety, but it has to compromise non-HMD users or the physical environment during usage. Our work is going to provide HMD users with a more immersive environment by turning off the alert from the physical environment, but keeping safety based on notifying bystanders of HMD users' playing area.

3 Guardian Awareness Techniques

As guardians set boundaries for the VR users to constrain their actions, our designs of the guardian awareness techniques aim to expose to bystanders how close they are to the guardians to help them avoid entering the zones of possible collision. To facilitate the usage of these techniques in everyday contexts, we base the designs on devices that bystanders are likely to carry around already. Augmented reality has been widely used to reveal hidden information in physical space (e.g. [13, 27]). Our first technique, *augmented reality*, directly visualizes the positions and overall shapes of guardians on bystanders' mobile phone camera feed. Although bystanders can see full guardian areas at once using this technique, they need to constantly process 3D visualizations, which can be more cognitively taxing [52] and distracting in comparison to lower-dimensional information displays [35]. This motivates us to devise three other techniques focusing on conveying one-dimensional guardian information. These techniques communicate the distance from the bystander to the closest point on the guardian. Inspired by prior research on obstacle alerts for mobile phone users [22], we employed three distinct modalities for the three techniques, *Visual Alert*, *Haptic Alert*, and *Auditory Alert*.

3.1 Augmented Reality

The *Augmented Reality* technique displays guardians as turquoise, three-dimensional barriers on bystanders' phone camera feed (Fig. 2), providing in-situ, intuitive visualizations of guardian positions and shapes. This design also allows bystanders to see the entirety of the guardians, given that they keep sufficiently distances from the VR users. However, in real-world scenarios, 3D visualizations may distract bystanders engaged in other activities on their phones.

3.2 Visual Alert

Visual Alert shows a flickering red bar at the top of the smartphone screen. Once a bystander enters the area within one meter from the guardian, the flickering frequency and color brightness of the bar begin to increase linearly as the distance between the bystander and the closest point on the guardian decreases (Fig. 3). This approach uses minimum visuals to inform bystanders of how close they are to invade guardians.

3.3 Haptic Alert

While visually simple, *Visual Alert* still requires looking at phone screens, potentially competing for visual attention from bystanders who are manipulating their phones' graphical interfaces. Therefore, we explore alerts that sit in the "background" [15] for everyday mobile phone operation, starting with *Haptic Alert*. This method leverages vibration on bystanders' smartwatches and modulate the vibration frequency and amplitude to communicate bystanders' distance to guardians. Similar to *Visual Alert*, vibration frequency and amplitude grows linearly as the bystander approaches the guardian, beginning when the bystander is one-meter away (Fig. 4).

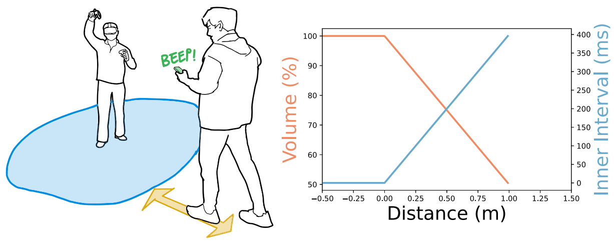

Figure 5: *Left: Auditory Alert* use beep sound to notify the bystander of their distance to the guardian. *Right:* The volume of the beep increases and the interval between two consecutive beeps decreases as the bystander gets closer to the guardian. The value of the volume axis indicates the percentage of the maximum volume of the device.

3.4 Auditory Alert

Our second "background" alert, *Auditory Alert*, plays a recurring beeping sound when the distance from the bystander to the guardian drops below one meter. Intervals between beeps get shorter and beeps get louder, linear to the distance between the bystander and the closest point on the guardian (Fig. 5). Using the auditory modality can avoid potential interference with bystanders' hand movements due to vibration when they are performing touch interaction on their phones. However, auditory alerts may be disruptive to other bystanders and the VR user.

4 Evaluation

Our study aimed at evaluating whether guardian awareness techniques could guide bystanders in circumventing the guardians to safely and efficiently reach their destinations. We focused on three aspects, (1) *invasion into guardians* to evaluate the techniques' efficacy in promoting safety, (2) *speed* and (3) *distraction* to understand whether the techniques might significantly hinder bystanders' normal activities, which could lead to non-adoption. These goals translated to the following research questions:
RQ1: Can guardian awareness techniques reduce guardian invasion rate of bystanders?
RQ2: Which guardian awareness techniques are the most efficient in helping bystanders circumvent guardians and reach their destinations?
RQ3: To what extent do guardian awareness techniques distract bystanders from tasks they are currently performing on their phones?

4.1 Participants

We recruited 15 participants (8 females, 7 males).Their ages were between 21 to 25 (M=22.8), and 10 of them had VR experience. All participants gave informed consent and were paid 20 CAD for their participation.

4.2 Task and Procedure

Subjects are introduced to the background and goal of the study, and they were given several minutes to get familiar to each guardian awareness technique.

One member of the research team, acting as the VR user, wore an HMD and performed regular VR interactions, including menu browsing and selection, in the experiment room. Participants were asked to cross the VR user as fast as possible while not entering the guardian, and not to have assumptions about the guardians' shape and size as they are randomly generated. The VR user did not move throughout study sessions. In each trial of the study, participants walked between two fixed locations (A and B) in the experiment room while avoiding a randomly generated guardian around the VR user. Experiment setup is shown in Fig. 6. Participants were aided by one of the four guardian awareness techniques, i.e. *augmented reality*, *visual alert*, *haptic alert* and *auditory alert*, or no technique at all (*baseline*). The experiment for each participant lasted 40 minutes. Time to complete each trip between the two locations (A to B or B to A) and paths of the trips were recorded.

To gauge the distraction that awareness techniques may induce, we asked participants to perform the tasks while typing on the phone (*typing*) and not typing (*not-typing*). In the *typing* conditions, participants typed sentences chosen from a dataset commonly used in mobile typing research [43] with a virtual keyboard on the phone while walking. The virtual keyboard did not auto-complete words nor correct typos to avoid introducing additional confounder variables to the typing test. A new sentence would appear when participants finished typing the current one. All keystrokes, including backspaces, were recorded for analysis.

The order of techniques were counterbalanced between participants following a Latin Square design. The order of *typing* vs. *not typing* were counterbalanced between participants. Under each condition, participants completed a round trip from location A to B and back to A. A new VR guardian was randomly generated each time participants reached either location A or B, thus resulting in two separate trials. Each participant completed 20 ($5 \times 2 \times 2$) trials in total. We introduce more details on guardian generation in Sec. 4.3

After the experiment, participants filled in a questionnaire asking for their subjective perceptions of the intuitiveness, distraction, clarity of the techniques with 7-point Likert scale. The questions included:
Q1 (Intuitiveness): I can understand this technique easily.(1: I cannot understand the technique even with an explanation, 7: I can understand the technique without explanation)
Q2 (Distraction): This technique is distracting me from the typing task.(Higher score means less distracting)(1: I cannot type when I use this technique. 7: I can type as smooth as without the technique)
Q3 (Clarity): I can easily understand my position relative to the guardian. (1: I cannot know how far I am away from the guardian at all, 7: I can know the exact position of the guardian)

4.3 Guardian Generation

In order to reduce learning effects between trials and conditions, we generated a new circular guardian with a random radius length and further perturb the shape with a random noise when the participant reached either the location "A" or "B". Centers of the generated guardians were fixed. Radii of guardians were sampled from a uniform distribution between 0.9 and 1.6 meters. We add randomness to the shapes of the sampled circles by perturbing the distance from 50 evenly sampled points on the circles to the centers with a uniform noise between -0.2 meters and 0.2 meters, and smooth the resulting curves with a low pass filter.

4.4 Environment and Apparatus

We conducted the study in a lab space of 4 meters by 4 meters. The VR user stood at the center of the room, with Point A and Point B each 2 meters apart from the VR user (Fig. 6 (A)). We set up three Kinect sensors for tracking.

We implemented *Augmented Reality*, *Visual Alert*, and *Auditory Alert* on a Samsung Galaxy S21 mobile phone. *Haptic Alert* was implemented on a Samsung Watch 4 smartwatch. Fig. 6 (B) illustrates the visual alert user interface used for the study with typing task. Pulse duration of visual alert was 50ms, of auditory alert was 100ms and of haptic alert was 40ms. We set up three Microsoft Kinect v2 depth cameras to track positions of participants using Creepy Tracker [38]. Control commands for visual, haptic, or auditory alerts were sent to the phone and smartwatch through a local wireless network. For *Augmented Reality*, positions of the participants were tracked by ARCore. To calibrate the coordinate system of ARCore and Creepy Tracker, markers denoting point A, point B and center of the guardian were on the floor. We used center of guardian as the

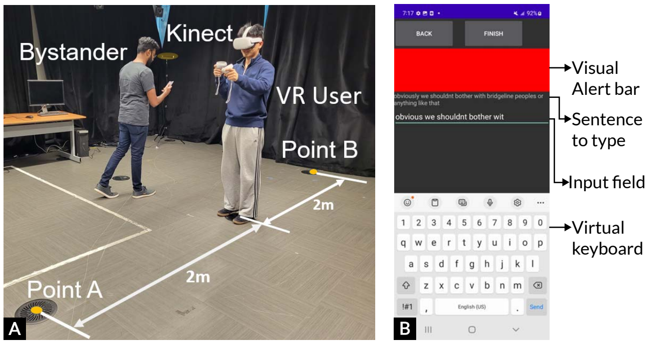

Figure 6: *(A)* Experiment setup. The bystander participant walked around the VR user, moving between point A and B. Kinect depth cameras were used to track participants' positions. *(B)* The phone interface used for the study, showing the *Visual Alert* technique.

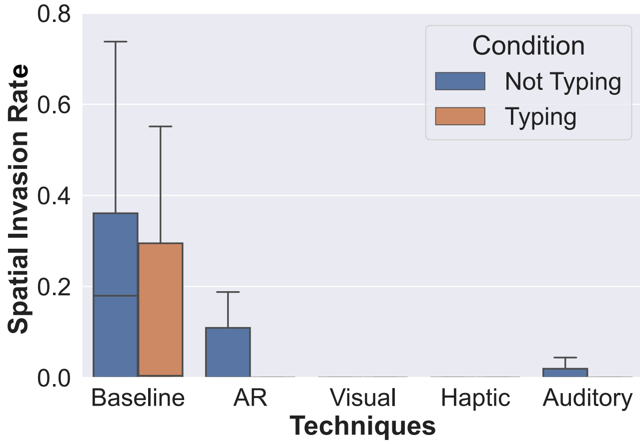

Figure 7: Boxplot showing the spatial invasion rates for baseline and the four techniques. AR is for *Augmented Reality*.

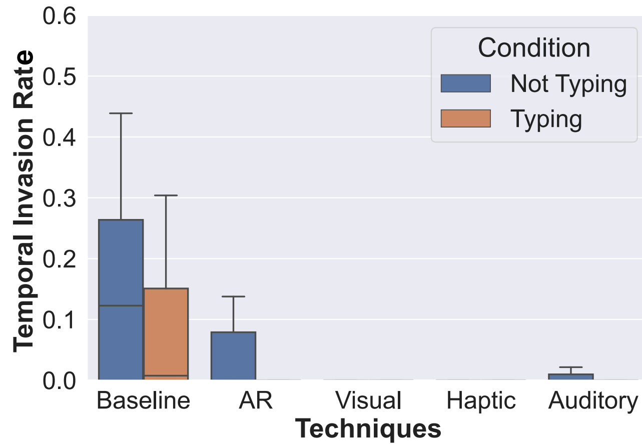

Figure 8: Boxplot showing the temporal invasion rates for baseline and the four techniques. AR is for *Augmented Reality*.

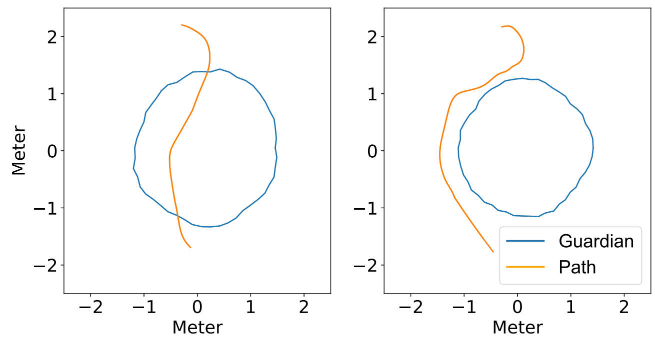

Figure 9: Visualizations showing the guardians and the traveling paths (*left*) without guardian awareness techniques and (*right*) with guardian awareness techniques. It shows the guardian's shape and position from a top-down view.

origin point in world space. Anchors were added in both ARCore and CreepyTracker to track those points in world space, the coordinate system was calibrated by matching the corresponding anchor points in Creepy Tracker and ARCore. We recorded participants' positions at a frequency of 25Hz with Kinect and 1Hz with ARCore.

5 Results

The analysis results will be presented in terms of (i) invasion of guardians (ii) task completion time (iii) typing performance (iv) subjective perceptions.

5.1 Invasion of Guardians

Before invasion rate analysis, we removed outlier points from the trajectory and applied a low-pass filter and linear interpolation to denoise and smooth the path. We measured invasion of guardians based on two metrics, spatial invasion rate and temporal invasion rate. Temporal invasion rate was defined as the time participants spent inside guardian areas over the task completion time. Spatial invasion rate was defined as the distance participants walked inside guardian areas over the total distance they travelled in each trial. As the invasion rates were not normally distributed, we applied the non-parametric Friedman test among four techniques plus baseline and Wilcoxon signed-rank test for post hoc tests.

5.1.1 Spatial Invasion Rate

Friedman test revealed significant differences in spatial invation rate between the four techniques and the baseline for both *non-typing* ($\chi^2(4) = 32.20, p < 0.001$) and *typing* ($\chi^2(4) = 10.74, p = 0.030$) conditions (Fig. 7). With Wilcoxon signed-rank test, we found significant reduction in spatial invasion rate when comparing all the four techniques with *baseline* for both *not-typing* (*Augmented Reality* $p = 0.014$, *Haptic Alert* $p < 0.001$, *Auditory Alert* $p < 0.001$), *Visual Alert* $p < 0.001$) and *typing* conditions (*Augmented Reality* $p = 0.017$, *Haptic Alert* $p = 0.049$, *Auditory Alert* $p = 0.011$, *Visual Alert* $p = 0.005$). The paths and guardian with and without using guardian awareness techniques are shown in Fig. 9 with visual alert technique. Pairwise comparison with posthoc Wicoxon test indicated *haptic*($p = 0.039$) and *visual*($p = 0.015$) alerts had less spatial invasion rate compared to *Augmented Reality* technique in *non-typing* condition. Moreover, Wilcoxon signed-rank test revealed significant reduction in spatial invasion rate when bystanders are typing in *baseline*($p = 0.026$) and *AR*($p = 0.046$) technique.

5.1.2 Temporal Invasion Rate

Similarly, Friedman test showed significant differences among the four techniques and the baseline in time invasion rate for both *not-typing* ($\chi^2(4) = 29.93, p < 0.001$) and *typing* ($\chi^2(4) = 11.98, p = 0.018$) conditions (Fig. 8). Wilcoxon signed-rank tests suggested

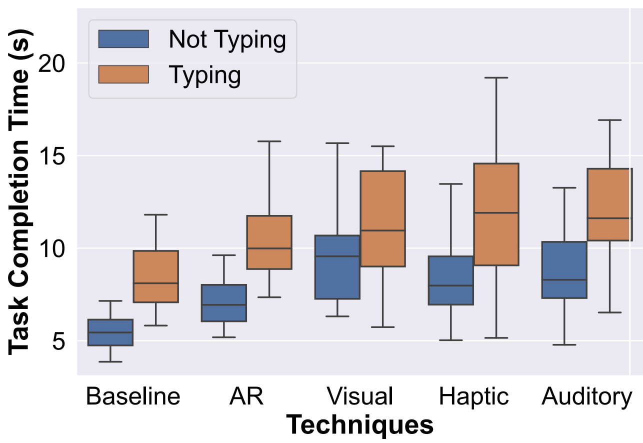

Figure 10: Boxplot showing the task completion time for baseline and the four techniques. AR is for *Augmented Reality*.

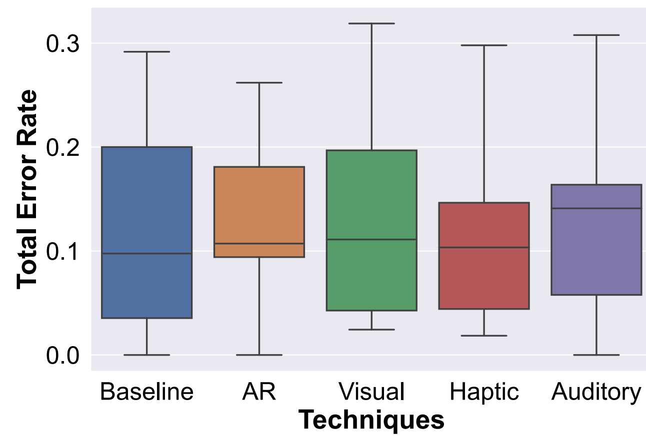

Figure 11: Boxplot showing the typing error rates for baseline and the four techniques. AR is for *Augmented Reality*.

that participants spent significantly less time in guardian areas with any of the four techniques when compared to *baseline* for both *not-typing* (*Augmented Reality* $p = 0.018$, *Haptic Alert* $p < 0.001$, *Auditory Alert* $p < 0.001$, *Visual Alert* $p < 0.001$) and *typing* (*Augmented Reality* $p = 0.006$, *Haptic Alert* $p = 0.024$, *Auditory Alert* $p = 0.011$, *Visual Alert* $p = 0.002$) conditions. Pairwise comparison with posthoc Wicoxon test indicated *Visual Alert* had less spatial invasion rate compared to *Augmented Reality*($p = 0.019$) technique in *non-typing* condition and *auditory*($p = 0.047$) alert in *typing* condition. Moreover, Wilcoxon signed-rank test revealed significant reduction in spatial invasion rate when bystanders were typing in *baseline*($p = 0.021$) and *AR*($p = 0.046$) technique.

5.2 Task Completion Time

Let t_A and t_B be the times when participants reached the point A and point B. Task completion time was defined as $|t_A - t_B|$. Absolute value was used since participant walked in A–B–A order, i.e., two task completion time were recorded each trip and always positive. Fig. 10 shows the distribution of task completion time of each technique in typing and non-typing conditions.

Paired t-tests were conducted and the result indicates typing condition could significantly increase the task completion time of baseline($p < 0.001$), Augmented Reality($p < 0.001$), haptic($p < 0.001$), auditory($p < 0.001$), visual($p < 0.001$) alert techniques.

Furthermore, typing and non-typing conditions were isolated and conducted with one way ANOVA test with paired t-test post hoc tests. In both typing($F_{4,145} = 6.25, p < 0.001$) and non-typing($F_{4,145} = 17.57, p < 0.001$) situations, significant difference was found between different techniques. Baseline took significantly shorter task completion time to reach the destination compared to Augmented Reality(Non-typing: $p < 0.001$, Typing:$p < 0.001$), haptic(Non-typing: $p < 0.001$, Typing:$p < 0.001$), auditory(Non-typing: $p < 0.001$, Typing:$p < 0.001$) and visual(Non-typing: $p < 0.001$, Typing:$p < 0.001$) techniques. In addition, Augmented Reality's task completion time was significantly shorter than haptic($p = 0.003$), auditory($p = 0.001$), visual($p < 0.001$) alerts in non-typing situation and shorter than auditory($p = 0.019$) and visual($p = 0.031$) techniques significantly in typing situation. There was no statistical significant difference between haptic, auditory and visual alerts.

5.3 Typing Performance

Following prior text-input research [37,46], we used speed and error rate to measure typing performance. Typing speed was calculated

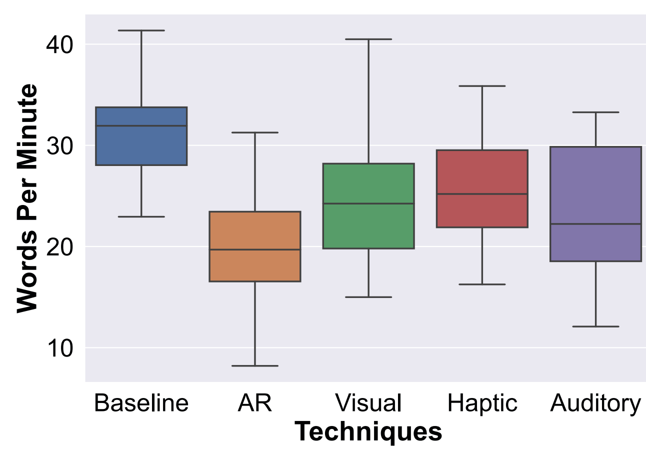

Figure 12: Boxplot showing the typing speed (Words Per Minute) for baseline and the four techniques. AR is for *Augmented Reality*.

as:

$$Word\ Per\ Minute\ (WPM) = \frac{|T|}{S} \times 60 \times \frac{1}{5}$$

where T is the length of the typed sentence and S represents the time used for completion. Error rates were calculated by:

$$Error\ Rate == \frac{IF + INF}{C + INF + IF}$$

where INF indicates the number of incorrect but not fixed characters, and IF means number of incorrect but fixed characters. C is the number of correct characters.

5.3.1 Error Rate

Fig. 11 illustrates the distributions of error rate for the four techniques and *baseline*. Error rates were not normally distributed, then non-parametric Frideman test on error rates ($\chi^2(4) = 0.98, p = 0.91$) did not find significant difference between the five conditions.

5.3.2 Typing Speed

Fig. 12 shows the distributions of WPM for the four techniques and *baseline*. One way ANOVA test found significant differences in typing speed between the five conditions ($F_{4,70} = 3.96, p = 0.006$).

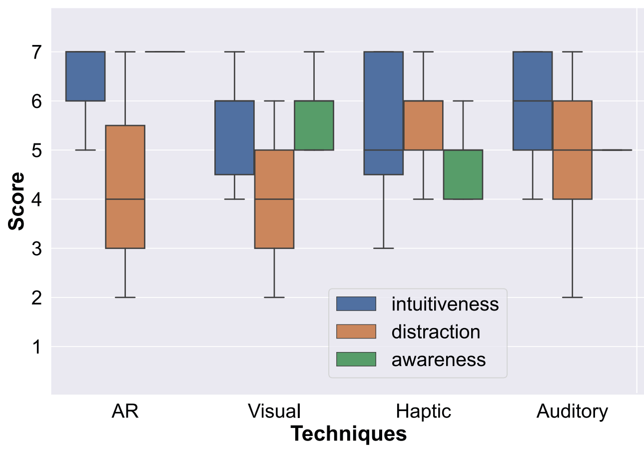

Figure 13: Subjective questionnaire results of each technique on intuitiveness, distraction and awareness. AR is for *Augmented Reality*.

Post-hoc paired t-tests showed that all techniques but *Haptic Alert* slowed down typing speed in comparison to *baseline*. Specifically, WPM of *baseline* ($M = 31.94, SD = 5.82$) was significantly higher than *Augmented Reality* ($p < 0.001, M = 20.59, SD = 6.73$), *Visual Alert* ($p = 0.003, M = 25.39, SD = 7.89$), and *Auditory Alert* ($p = 0.027, M = 24.80, SD = 9.42$), but not significantly different from *Haptic Alert* ($p = 0.004, M = 27.20, SD = 8.35$). Moreover, WPM with *Haptic Alert* was significantly faster than with *Augmented Reality*.

5.4 Subjective Perceptions

We gauged participants' subjective perception about the intuitiveness, distraction and clarity of the techniques based on their questionnaire responses (Fig. 13). Since questionnaire metrics were discrete variables, we applied non-parametric Frideman test and Wilcoxon signed-rank tests as post-hoc test for the following analysis.

Intuitiveness: Significant difference($\chi^2(3) = 15.39, p = 0.002$) was found between the four techniques for intuitiveness. Post-hoc test results showed that *Augmented Reality* ($M = 6.53, SD = 0.62$) was considered the most intuitive method and was rated significantly higher than *Haptic Alert* ($p = 0.007, M = 5.46, SD = 1.31$), *Auditory Alert* ($p = 0.015, M = 5.73, SD = 1.06$), and *Visual Alert* ($M = 5.4, SD = 1.02, p = 0.003$) techniques. No statistically significant difference was found between other techniques ($p > 0.05$).

Distraction: The four techniques were rated significantly differently in distraction as suggested by Frideman test ($\chi^2(3) = 10.45, p = 0.015$). Wilcoxon signed-rank posthoc tests showed that *Haptic Alert* ($M = 5.47, SD = 1.15$) was significantly less distracting than *Visual Alert* ($p = 0.007, M = 4.13, SD = 1.26$) and *Augmented Reality* ($p = 0.016, M = 4.13, SD = 1.54$). No statistically significant difference was found between other pairs of techniques.

Clarity: Friedman test indicated that the four techniques had significantly different ($\chi^2(3) = 29.58, p < 0.001$) ratings on their perceived ability to communicate the position of the participant relative to the guardian. Not surprisingly, participant reported that they felt *Augmented Reality* ($M = 6.86, SD = 0.34$) provided the most effective compared to *Haptic Alert* ($p < 0.001, M = 4.93, SD = 0.85$), *Auditory Alert* ($p < 0.001, M = 5.13, SD = 0.50$), and *Visual Alert* ($p < 0.001, M = 5.33, SD = 1.07$).

6 Discussion

Our study found guardian awareness techniques can significantly reduce bystanders' invasion into guardian areas (time in guardian areas reduced to as low as 0.4% of total walking time) to promote safety (RQ1). *Augmented Reality* can help participants circumvent guardians and reach their destinations at least 14% faster than *Visual Alert*, *Haptic Alert*, and *Auditory Alert* (RQ2). Guardian awareness techniques did not introduce more errors in typing, but three of the four techniques slowed down typing speed. *Haptic Alert* did not induce a significant drop in typing speed, suggesting that it could be the least distracting technique for bystanders engaged in other tasks on their phones (RQ3).

6.1 Effectiveness, Efficiency, Distraction, and Trade-off

While *Augmented Reality* clearly presents a larger amount of information about guardians, such advantage only translates to a gain in its efficiency in guiding bystanders, but not its effectiveness in helping them avoid guardian areas. In fact, *visual alert* achieved lower invasion rates than *Augmented Reality* when participants were not typing. This suggests that simple one-dimensional, distance-based alerts can be as effectively as three-dimensional, in-situ visualizations for bystanders to steer off guardian areas. We also observed that some participants relied only on an initial overview of the guardian from the augmented reality view to plan the full paths to destinations. After seeing the initial overview, they stopped paying attention to the phone while walking, which led to more invasion. This observation was corroborated by our data, which showed that participants had lower temporal and spatial invasion rates with *Augmented Reality* when they were asked to focus on the phone's screen to type. Future work can look into combining augmented reality and distance-based alerts to prevent bystanders from being overconfident about the paths they choose and hence exposing themselves to risks.

Augmented Reality is the most efficient technique among all. It may gain this advantage partially because of its ability to expose full guardians immediately, enabling bystanders to plan ahead and choose more efficient paths. In contrast, bystanders can only explore the guardians along the way with distance-based alerts.

Objective metrics, including typing speed and error rate, and participants' subjective perceptions suggest that *Haptic Alert* is the least distracting technique among the four options to bystanders engaged in other tasks on phones. These results support our hypothesis during the design process that "background" techniques, which do not actively ask for visual attention, induce less distraction. On the contrary, the rich, dynamic graphics that *Augmented Reality* presents tends to distract bystanders away from tasks at hand, as P5 reported, *"the negative side of AR is that various kinds of content take up the whole phone screen, making it hard to focus on typing."* The difference in distraction between the haptic and auditory alerts corroborates earlier research that found haptic alerts considered more appropriate and less distracting than auditory alerts for drivers [25].

Our analysis across the effectiveness, efficiency, and distraction metrics highlight the trade-off in designing and choosing guardian awareness techniques for real-life scenarios.

6.2 Design Implications

The efficiency-distraction trade-off indicate that we should consider bystanders' current activities when choosing guardian awareness techniques. If bystanders are already working on their phones when they approach VR users, *Haptic Alert* can be used to minimize distraction while still ensuring safety. If bystanders are not currently using their phones, we can send them a notification that gives them the choice to start *Augmented Reality* for a speedier clearing of guardian areas. If the notification is ignored, *Haptic Alert* is automatically turned on.

Our one-dimensional guardian awareness techniques operate with different modalities. Each modality could perform differently depending on the user and the context of usage. For example, *auditory alert* could be distracting to others in public spaces and to the VR user. Users of *visual alert* and *augmented reality* need to keep holding their phones, which could lead to physical fatigue. Some people are less sensitive to the vibration of *Haptic Alert*. Our future work will study automatic technique selection based on current contexts, for example, turning on *Auditory Alert* only when the bystander is wearing headphones.

6.3 Limitations and Future Work

We discuss the limitations and future work of this paper, with respect to our technique design and evaluation methodology.

6.3.1 Techniques

Our guardian awareness techniques are based on devices carried by the bystanders. An alternative approach is to have VR users explicitly emit signals about their guardians, for example, with LED light rings display an effect similar to *Visual Alert* on the VR headset. We are particularly interested in the result of deploying *Augmented Reality* technique onto AR glasses or projecting the guardian to the ground. Smartphone screen size is a limitation of *Augmented Reality* technique, which might have an impact on the result.

Our distance-based techniques, including *Visual Alert*, *Haptic Alert*, and *Auditory Alert*, do not yet distinguish between multiple VR users. Future work could encode directionality information into the feedback to help bystanders navigate around multiple VR guardians.

While we specifically focus on providing awareness to bystanders in this paper, previous research [31, 44] studied project bystanders into the VR environment. Our approach can be combined with previous work to build bi-directional notifications to further improve VR safety. Yang et al. [50] found deploying a negotiation channel for guardian positions and sizes between co-located VR users and bystanders could improve flexibility in space usage. We plan to design and deploy notifications for VR users when the bystanders are close to or entering the guardian to facilitate this negotiation process.

6.3.2 Evaluation

We assumed interaction with graphics user interface is the most common mode of using mobile phones. Therefore, part of our design rationale is to reduce visual distraction. Recognizing that other modalities, such as the auditory and tactile modalities, are also frequently involved in everyday phone usage, our future work will explore the effectiveness and distraction levels for non-visual and multi-modal activities on phones, e.g. watching videos, video chat, playing games, etc.

Our study only focused on the case with one bystander and one guardian. Additionally, our study task used simplified movement trajectories around VR users, asking participants to travel between two fixed points. We are interested in experimenting with more realistic environments, e.g. with multiple bystanders and obstacles, and with more complex routes assigned to bystanders.

In our study, the VR user performed actions requiring only small-range arm movements, including menu browsing and selection, and no locomotion in the experiment room. Some VR applications, such as sports games, need players to be more physically active. Therefore, bystanders can gain information about guardians from the movement of the VR users. Future studies could involve confederate VR users moving around and performing larger-range arm movements in the experiment environment.

7 Conclusion

With the increasing prevalence of VR in everyday environments, bystanders unaware of the shapes and positions of VR guardians are exposed to the risk of collision with VR users. We designed and evaluated four guardian awareness techniques for bystanders to learn their relative positions with guardians and choose safe paths around VR users. Our techniques use standard mobile computing devices, including phones and smartwatches. The first technique, *Augmented Reality*, visualize guardians in situ around VR users through augmented reality on bystanders' phones. The other three techniques, *Visual Alert*, *Haptic Alert*, and *Auditory Alert*, use different modalities on phones and smartwatches to notify bystanders of their distances to guardians. We evaluated these techniques concerning their effectiveness, efficiency, and level of distraction to bystanders engaged in other activities on their phones. Results showed that all techniques could significantly reduce the chance bystanders enter guardian areas, *Augmented Reality* allowed bystanders to reach destinations faster, and *Haptic Alert* posed the slightest distraction. We discuss the trade-off between efficiency and distraction and suggest choosing guardian awareness techniques based on bystanders' current engagement level with their phones.

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