Re-Evaluating VR User Awareness Needs During Bystander Interactions

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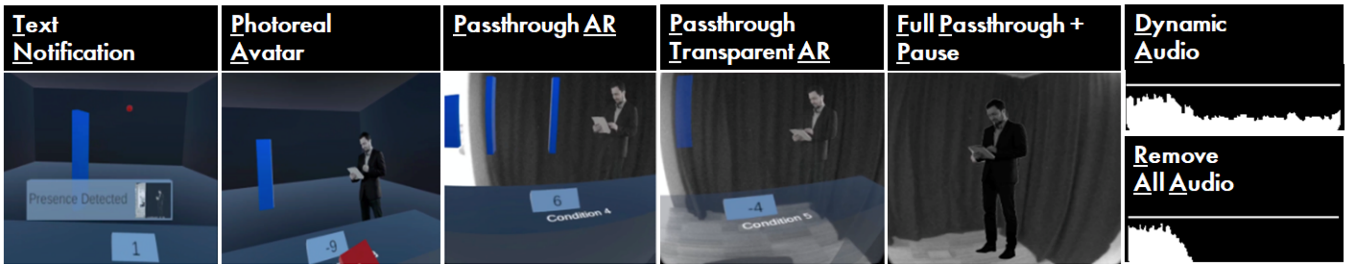

Figure 1: The awareness systems designed to facilitate bystander-VR user interactions used in our study. The visual awareness systems are: text notification (TN), photoreal avatar (PA), three variations of passthrough views (PAR, PTAR, FPP). The aural awareness systems (of which a visualisation of the change in in-VR audio volume is shown) are: dynamically lowering (DA) or removing (RAA) the VR application's volume. A full description of these is provided in Section 3. We evaluated the usability and impact on a VR user's sense of presence of these, and assessed their usage across 14 bystander-VR user interaction scenarios.

ABSTRACT

Virtual reality (VR) users are often around bystanders, i.e. people in the real world the VR user may want to interact with. To facilitate bystander-VR user interactions, technology-mediated awareness systems have been introduced to increase a user's awareness of bystanders. However, while prior works have found effective means of facilitating bystander-VR user interactions, it is unclear when and why one awareness system should be used over another. We reviewed, and selected, a breadth of bystander awareness systems from the literature and investigated their usability, and how they could be holistically used together to support varying awareness needs across 14 bystander-VR user interactions. Our results demonstrate VR users do not manage bystander awareness based solely on the usability of awareness systems but rather on the demands of social context weighted against desired immersion in VR (something existing evaluations fail to capture) and show the need for socially intelligent bystander awareness systems.

CCS CONCEPTS

- **Human-centered computing → Virtual reality**.

KEYWORDS

Virtual Reality, Mixed Reality, Augmented Reality, Bystander-VR User Interactions, Interruptions, Awareness, Context Awareness

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1 INTRODUCTION

Virtual Reality (VR) is often used in shared, social settings [41]. However, interactions between VR users and bystanders (individuals physically near a VR user but who cannot directly interact with their virtual environment) remain problematic [29, 35, 39, 41]. Central to this is the occlusive nature of VR headsets which introduce significant barriers to a user's awareness of, and interaction with, bystanders. To overcome this, research and industry are increasingly examining technology-mediated reality awareness systems that support usage of VR devices by automatically increasing a user's awareness of and facilitating interactions with bystanders [10, 29, 32, 34–36, 38, 40, 50]. Yet, while prior works have established

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how individual, singular *bystander awareness systems* can successfully notify a VR user of bystander co-presence [10, 29, 32, 38, 45, 50] or facilitate interactions [9, 20, 29, 40, 52], at present, we lack a holistic understanding of how we might bring together disparate work on bystander awareness into cohesive systems that provide the *"right"* awareness to the VR user (i.e. the need for awareness to vary based on the bystander's presence, proximity, actions, etc). This is due to prior works focusing primarily on whether a tested awareness system (a) achieves some level of desired increased awareness, and (b) what impact, if any, this has on the VR user's sense of presence [10, 29, 32, 45, 50].

Crucially, then, while prior works have evaluated the usability and impact on immersion of awareness systems, they have failed to clarify how disparate approaches towards reality awareness might be utilized in conjunction to optimally balance awareness and immersion needs at any given point. As a consequence of the evaluation methodologies used in past works, despite outlining many ways in which bystander awareness can be increased, prior works cannot say, for example, given a range of bystander awareness systems (each known to increase awareness differently with varying trade-offs) *which* a VR user would use, *when* and *why*. Therefore, our work extends the real-world applicability of prior work by studying how contextual factors, such as the interaction modality or the bystander's actions/position relative to the VR user, impact the preferred choice of the bystander awareness approach.

We present the results of the first study (N=16) to holistically evaluate the varying need for bystander awareness across 14 bystander-VR user interaction scenarios (frequently occurring, real-world interactions between bystanders and VR users reported in past works [4, 41]). The study consisted of 2 parts. The first part, the *Baseline Usability* evaluation, was designed to familiarise participants with 7 awareness systems designs we implemented, based on a review of the literature, that varied in the extent and detail to which they informed and facilitated bystander co-presence: a text notification, photoreal avatar, 3 variations of passthrough views and dynamically lowering or removing in-VR audio. This provided an evaluation of the awareness systems modelled after the methodologies used in prior works (e.g. [10, 29, 32, 40]). The second part, the *Assessing Awareness Needs* evaluation, then used our novel evaluation methodology to investigate how, when and why participants would use the 7 bystander awareness systems to increase their awareness during 14 bystander-VR user interaction scenarios through a think aloud exercise.

Our results demonstrate the shortcomings of existing evaluations of bystander awareness systems by showing VR users do not manage awareness based solely on the usability of awareness systems but rather on the demands of social context weighted against desired immersion in VR - something existing evaluations of awareness systems have failed to capture. Additionally, we define 4 personas for how VR users expect bystander awareness to be provided and identify *critical moments* within bystander-VR user interactions which provoke a change in a VR user's awareness needs. We close by discussing the need for bystander awareness evaluation methodologies to move towards more holistic and ecologically valid approaches that capture experience with the systems over time in a variety of interaction contexts - an approach better suited for the development of socially intelligent bystander awareness systems.

2 RELATED WORK

2.1 The Importance of Facilitating Bystander Awareness & Interactions

Dao et al. were the first to explore bystander-VR user interactions in the home and focused on categorising *"VR fail videos"* posted online to understand why accidents occurred whilst using VR [4]. They identified various types, and causes, of failure (e.g. accidental collisions between VR users and bystanders) and illustrated both the impact that a lack of bystander awareness has on safety (e.g. a VR user colliding with an unknown bystander) and necessity of reality awareness as a safety-critical feature in VR [8]. Subsequently, O'Hagan et al expanded upon Dao et al's work by conducting an exploratory survey to capture a more diverse set of in-the-wild bystander-VR user interactions [41]. Their results highlighted prevalent bystander-VR user interaction archetypes and examples of specific, frequently occurring, bystander-VR interactions and outlined specific problems encountered whilst interacting. Crucially, O'Hagan et al showed some bystanders, that a VR user is unaware of, will abuse their position of power (e.g. by pushing the VR user), further demonstrating the necessity of bystander awareness as a safety-critical of VR headsets.

2.2 Notifying a VR User of Bystander Existence

Due to the occlusive nature of VR headsets interactions with people in the user's surrounding environment can be problematic [10, 18, 29, 41]. To overcome this, research has developed cross-reality awareness systems to automatically detect bystanders and inform VR users of their co-presence. McGill et al. were the first to investigate this by developing a system to automatically notify a VR user of bystanders by contextually blending photoreal avatars of bystanders into the VR scene [29]. Their approach, however, was found to significantly disrupt the VR user's sense of presence and they concluded less disruptive methods were required.

Since McGill et al's formative paper, much work has investigated a range of approaches to notify a VR user of bystander co-presence. Research has investigated the feasibility of text [10, 38, 42, 54], audio [38, 40] and haptic notifications [7, 10], various avatar aesthetics [9, 11, 20, 29, 32, 38, 45, 50], continuous vs temporary notification designs [35, 38, 54] and contextually increasing the amount of reality incorporated within the VR scene [9, 29]. And while these works have proven VR users can successfully be notified of bystander existence, they are limited by focusing primarily on evaluating (a) whether the built system can successfully notify the VR user of bystander co-presence, and (b) what impact this has on the user's sense of presence [36, 40]. As such, we lack a holistic understanding of how awareness systems might effectively fit together and be used in conjunction, so that users can experience bystander awareness which adapts to their context and optimizes for trade-offs around awareness/immersion in the process.

2.3 Facilitating Bystander-VR User Interactions

Research has also investigated the design of systems which look beyond notification of bystander co-presence, towards how to facilitate an interaction with a bystander the VR user is aware of. Yang et al., observing VR users and bystanders often share the same

Technique	*Description*	*Modality*	*Information Conveyed*	*Examples*
Text Notification (TN)	A 5 second temporary text notification to notify bystander entry/exit (an image of the bystander/room embedded within the notification) and a persistent UI icon present while the detected bystander was in the room	Visual	Bystander identity	[38, 42, 54]
Photoreal Avatar (PA)	Augments a photoreal avatar of the bystander into the virtual environment	Visual	Bystander identity Bystander position relative to VR user	[29, 34, 50]
Passthrough AR (PAR)	Switch to an AR version of the game (e.g. only essential game objects remain, everything else is replaced with the passthrough view)	Visual	Bystander identity Bystander position relative to VR user Passthrough of surrounding environment	[9, 29]
Passthrough Transparent AR (PTAR)	Switch to an AR version of the game with added transparency to remaining content (e.g. only essential game objects remain and are made transparent, everything else is replaced with the passthrough view)	Visual	Bystander identity Bystander position relative to VR user Passthrough of surrounding environment	[9, 29]
Full Passthrough + Pause (FPP)	Switch to a full passthrough view and pause the game	Visual	Bystander identity Bystander position relative to VR user Passthrough of surrounding environment	[11, 41, 50]
Dynamic Audio (DA)	Automatically lower VR application audio to 25% of the starting volume	Aural	Bystander voice Noise in surrounding environment	[38, 40]
Remove All Audio (RAA)	Lower all application audio to 0%	Aural	Bystander voice Noise in surrounding environment	[38, 40]

Table 1: A summary of the design of our awareness systems

physical space [52], developed the *ShareSpace* system to explore how a VR user and bystander might coexist in a physical space by allowing the bystander to section off areas of the real world as their own. Scavarelli et al. also investigated how to enable sharing of the same physical space and developed notifications to prevent accidental collisions from occurring [43]. Meanwhile others have investigated how a VR user's in-VR audio might be manipulated to facilitate a verbal interactions [38, 40].

However, these works are again limited by focusing their evaluation on the success of the built system to facilitate a single considered interaction. As such, they ignore the broader range of potential interactions and cannot say how, when, or why a VR user might use one approach over another. While some have proposed VR users will select the awareness system which sufficiently increases awareness whilst minimally disrupting presence [10, 29], recent works have established this assumption is incorrect [32, 35, 38, 40] suggesting the interaction itself, in part, necessitates the degree of awareness desired by a VR user. Absent, however, is an understanding of the influence of interactivity on awareness needs, and how we might map awareness systems across *"low, balanced, and full awareness states"* [40] to best accommodate different types of bystander-VR user interactions.

3 DESIGN OF OUR AWARENESS SYSTEMS

Based on a review of the literature, we implemented 7 bystander awareness systems that covered the current state of the art, most promising approaches, and varied in the extent and detail to which they inform and facilitate bystander co-presence. Our approaches (Figure 1) are summarised in Table 1. All approaches were designed to minimise unnecessary exits from VR. All contained identifiable information about the bystander, as prior work has shown some users will exit VR in the absence of this information [38]. All persisted for the entire duration of the bystander's co-presence to ensure the user did not exit VR to check if the bystander was still there [41]. Aurally, we included *Dynamic Audio (DA)* as a partial increase of awareness and *Remove All Audio (RAA)* as the aural equivalent of switching to full reality. Prior work has shown both are effective at facilitating interactions [38, 40]. Visually, *Text Notification (TN)* was included as prior work has shown some consider it sufficient for increasing awareness [38]. We included 3 variations of passthrough views (*Photoreal Avatar (PA), Passthrough AR (PAR), Passthrough Transparent AR (PTAR)*), augmenting increasing amounts of reality into virtual environment, due to the prevalence of passthrough-based approaches in past works [9, 11, 29, 50] and commercial VR devices [33, 34]. We included *Full Passthrough + Pause (FPP)* as the visual (and aural) equivalent of switching to full reality without removing the headset (e.g. [33]).

3.1 Awareness System Implementation Details

3.1.1 ***Wizard of Oz Approach:*** We based our implementation on prior works [9, 20, 38, 40] thus used a wizard of oz [16] approach where participant's exposure to the awareness systems were triggered on a timer to simulate bystander detection. This provided greater reliability and repeatability in the events participants were exposed to, as it ensured the point at which exposure to an awareness system began and the length of the exposure to the awareness system was fixed for all participants. The timings used and condition lengths are described in full in Section 4.2.1.

3.1.2 ***Fading Awareness In/Out:*** As sharp transitions between virtuality and reality can be disruptive for users [19], as suggested in prior works [29, 32, 38], all our approaches used a fading effect to add/remove awareness. For *DA* and *RAA* a linear interpolation method was used to gradually alter volume over a 0.5 second period. For *PA* the avatar's opacity faded in/out over 0.5 seconds. For *PAR, PTAR, FPP* the content replaced by the passthrough view turned black then faded into passthrough over 0.5 seconds (and used the same effect in reverse to return to virtuality). For *TN*, we followed Rzayev et al's recommendations [42], so the notification spawned in front of the user then moved in closer and followed the user's gaze, then was removed by moving away from the user and disappearing.

3.1.3 ***The Bystander:*** For the bystander in the visual conditions, we used a creative commons video of a man on a green screen which we converted to black and white to match the passthrough black and white view of the Oculus/Meta Quest 2 headset used during the study. Chroma key compositing was then used to augment the bystander into the VR user's virtual environment (within the VR scene) and view of reality (within the passthrough view). The bystander's position and scale was consistent across the conditions and was positioned/scaled to appear realistically with an appropriate depth and height.

4 BASELINE USABILITY EVALUATION: STUDY DESIGN

To understand how VR user awareness needs vary across interactions with bystanders, and what motivates any varying need in awareness, we designed a study consisting of 2 parts. The first part, the *Baseline Usability* evaluation, was designed to familiarise participants with our 7 awareness systems and for the first time evaluated, through a study modelled after the methodologies used in prior works [10, 29, 32, 38, 40, 50], a breadth of different awareness systems together, enabling us to draw direct comparisons regarding their efficacy. The second part, the *Assessing Awareness Needs* evaluation, then used our novel evaluation methodology to investigate how, when and why participants would use our awareness systems to increase their awareness during a range of bystander-VR user interactions. The study used a within-subjects design where every participant first completed the *Baseline Usability* evaluation then completed the *Assessing Awareness Needs* evaluation. This ensured participants had the intended learning effects (from the *Baseline Usability* evaluation) necessary to complete the *Assessing Awareness Needs* evaluation, and is an approach widely used within the literature (e.g. [53]). The design and results of the *Baseline Usability* evaluation follow (Sections 4 & 5) and the design and results of the *Assessing Awareness Needs* evaluation in Sections 6 & 7.

4.1 Experimental Task: Design of our Game Task

To ensure ecological validity, we evaluated our awareness systems using a primary task which recreated the affordances of typical home VR gaming usage. We developed visually and aurally demanding game task, requiring some player movement and direct interaction with the virtual environment. This created an experience with high levels of attention demand that would stress the design of the awareness systems during their evaluation. Prior work has shown application type can influence attitudes toward bystander awareness systems [7, 38], therefore we designed our experience to be representative of typical, current, consumer applications (e.g. games) [15, 36, 46].

The game was designed as a fixed, room-scale experience where users predominantly looked forwards and occasionally to their right. This ensured, by design, participants faced the direction our awareness systems were fixed to appear, and is an approach used in prior works [29, 32, 50]. The game's task was to throw cubes at moving targets to score points within a fixed time limit (similar in game design to [32]) and was chosen as a simple, yet effective, way of creating engaging gameplay [48]. To add variety to the gameplay, targets were randomised by shape (either cube or cuboid) and movement pattern (either stationary, moving left-to-right in front of or away-and-towards the user) with parameters for these being randomly selected from a range decided by the researchers during playtesting. The game's audio consisted of persistent, non-diegetic background music and one-off, diegetic sound effects emitted when a target was destroyed. A video demonstration of the game is shown here[1].

4.2 Experimental Conditions and Questionnaire Metrics

4.2.1 ***Experimental conditions:*** Our study's first part had 8 conditions: 1 for each of the 7 awareness systems, presented in Section 3, and a *baseline* condition (no awareness system) and consisted of 2 phases: a *training* and an *evaluation* phase. The training phase introduced each condition, to ensure participants were familiar with all awareness systems before evaluating any of them. During this phase, 1 condition (1 session of the game) lasted 45 seconds with 25 seconds exposure to the awareness system (starting after 10 seconds). Before starting each condition, participants were introduced to the condition. The evaluation phase assessed each condition, during which 1 condition lasted 90 seconds with 60 seconds exposure to the awareness system (starting after 20 seconds). After each condition ended the participant removed the headset and completed a questionnaire. Condition order was counterbalanced using a balanced Latin square approach.

4.2.2 ***Questionnaire Metrics:*** We designed a questionnaire, based on similar evaluations in prior works [29, 32, 38, 40, 50], to evaluate our awareness systems' usability and impact on sense of presence. All questions used a 7-point Likert scale. We did not ask the usability questions for the baseline as the questions were not applicable.

- ***Usability Statements:*** we evaluated usability using 8 questions. To what extent participants agreed (1=strongly disagree, 7=strongly agree) the awareness system: (1) *"was disruptive"*, (2) *"was frustrating"*, (3) *"was urgent"*, (4) *"felt natural"*, (5) *"was easy to understand"*, (6) *"was informative"*, (7) *"improved their ability to communicate with a bystander"*, (8) *"made you too aware of the real world"*.
- ***Presence Questions:*** we evaluated presence using the *"Sense of Being There"* and *"Involvement"* subsets of the IPQ questionnaire [44] and the following question: *"How much did it seem as if you and the person you saw/heard were together in the same place?"* taken from the TPI questionnaire [24, 25] (1=not at all, 7=very much).

4.3 Experimental Procedure: Baseline Usability Evaluation

Upon arrival the study's purpose was explained and a consent form and a demographic questionnaire were given to the participant. Participants were told they would play a VR game and experience 7 awareness systems we designed to increase their awareness of a nearby non-VR person (who they would see in several conditions and were to assume represented a known person to them). A demonstration video of the game was then shown and its controls explained. Participants were then instructed where to stand and shown (if required) how to put wear the headset. A Meta/Oculus Quest 2 headset was used to conduct the study.

Participants then began the training phase, during which they were told to set the headset's system volume to a comfortable but immersive level - most set volume to around 60%. After the training phase, participants were instructed to remove the headset and the experimenter set up the evaluation phase. After evaluating all conditions, participants were asked to rank order the awareness systems from best to worst (without a specific metric) and were

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[1] https://www.youtube.com/watch?v=pP-ORj49XWU

Usability Questions	*(1) Text Notification (TN)*	*(2) Photoreal Avatar (PA)*	*(3) Passthrough AR (PAR)*	*(4) Passthrough Transparent AR (PTAR)*	*(5) Full Passthrough + Pause (FPP)*	*(6) Dynamic Audio (DA)*	*(7) Remove All Audio (RAA)*	**Friedman Test**	***Wilcoxon Post-hoc*** *($p<0.0024$)*
Was disruptive	5.31 (2.08)	3.25 (1.75)	4.06 (1.89)	4.62 (1.87)	6.62 (0.6)	3.31 (2.05)	3.69 (1.69)	$\chi^2(6) = 34.33$, $p<0.0024$	5-2, 5-3, 5-4, 5-6, 5-7
Was frustrating	5.12 (1.65)	2.94 (1.78)	3.19 (1.81)	4.19 (2.07)	5.31 (1.65)	2.62 (1.65)	2.94 (2.11)	$\chi^2(6) = 27.02$, $p<0.0024$	1-6, 5-6
Was urgent	4.81 (1.84)	3.56 (1.66)	4.62 (1.93)	4.56 (1.9)	6.00 (1.7)	3.19 (1.51)	2.94 (1.78)	$\chi^2(6) = 27.54$, $p<0.0024$	5-6, 5-7
Felt natural	3.00 (1.7)	4.88 (1.76)	4.50 (1.77)	5.06 (1.64)	4.12 (2.06)	5.25 (1.64)	4.69 (1.86)	$\chi^2(6) = 33.49$, $p<0.0024$	1-6
Was easy to understand	5.62 (1.17)	5.94 (1.03)	6.00 (1.27)	6.38 (0.7)	6.38 (0.78)	4.75 (2.05)	5.19 (1.63)	$\chi^2(6) = 11.95$, $p=0.06$	N/A
Was informative	4.38 (2.03)	5.69 (1.21)	5.56 (1.54)	6.19 (0.73)	6.50 (0.71)	4.81 (1.94)	4.38 (1.65)	$\chi^2(6) = 21.80$, $p<0.0024$	N/A
Improved communication	2.81 (1.59)	4.69 (1.45)	5.00 (1.62)	5.69 (1.31)	6.06 (1.09)	5.50 (1.06)	5.62 (1.54)	$\chi^2(6) = 32.66$, $p<0.0024$	1-4, 1-5, 1-6, 1-7
Too aware of real world	2.50 (1.5)	2.31 (0.98)	4.25 (2.02)	4.62 (1.93)	5.31 (2.08)	2.81 (1.84)	3.00 (1.8)	$\chi^2(6) = 26.50$, $p<0.0024$	1-5, 2-4, 2-5

Table 2: Mean (standard deviation) values, and significant differences, for our usability evaluation (1=strongly disagree, 7=strongly agree). A heatmap on the mean (standard deviation) ranges from white (lowest) to purple (highest) based on the scale of the measure. Of note is *TN* which disrupted and frustrated users without improving communication with the bystander.

then asked to describe how they ranked their preferences (e.g. by which metric). Participants were then given the opportunity to take a break before beginning the study's second part.

4.4 Participant Demographic Data

Participants were recruited using social media and mailing lists. 16 participants completed the study (5 female, 11 male) aged between 19 and 33 years of age (M=23.13, SD=3.70). Participants indicated they had prior experience with VR (M=4.0, SD=1.10; 5-point Likert scale; 1=None; 5=A lot) with all having, at least, *"a little (2)"* prior experience using VR.

5 BASELINE USABILITY EVALUATION: RESULTS

Analysis: For the Likert-scale questions we calculated the mean and standard deviation values then used a Friedman test to find significant differences between factors and performed pairwise comparisons using Wilcoxon Signed Rank tests with Bonferroni corrected p-values. For the preference rankings, a Friedman test was used to test for significant differences and pairwise comparisons performed using Wilcoxon Signed Rank tests with Bonferroni corrected p-values. The average ranking score for each approach was calculated and participants' comments justifying their rankings were coded using initial coding [3] where participants' statements were assigned emergent codes over repeated cycles with the codes grouped using a thematic approach. A Google Pixel 4a was used to record participant qualitative comments and transcribe them. A single coder performed the coding (2 cycles) and reviewed the coding with one other researcher.

5.1 Usability Evaluation Results

The usability statements' mean, standard deviation values and statistical differences between the pairwise comparisons are summarised in Table 2. Individual factors are discussed, in turn, below.

5.1.1 ***Disruptive:***

Generally, the more reality incorporated into the user's virtual environment the more disruptive the condition was said to be (e.g. *FPP* incorporated the most reality and so was considered the most disruptive). Surprisingly, however, *TN* was considered the second most disruptive condition, scoring comparably to *FPP*. Significant differences between *FPP* and every condition except for *TN* reinforce this and participant comments highlight why TN was considered disruptive. This was, 7 participants said its *P12: "in your face, unavoidable nature"* meant, despite being temporary, it was difficult to ignore and so impacted their experience.

5.1.2 ***Frustrating:***

The conditions scored similarly in frustration as they did disruption. Generally, the more reality incorporated into the virtual environment the more frustrating the condition was said to be. Again, *TN* was the exception to this, with participants again citing their difficulty ignoring it to be frustrating. However, unlike disruption, only 2 significant differences were found between the conditions: between *DA* and *TN* and between *DA* and *FPP*. These were significant differences between the 2 most frustrating conditions (*TN* and *FPP*) and the least frustrating condition (*DA*). *FPP* again scored highest with participants citing the forced switch to reality to be their main issue with it.

5.1.3 ***Urgency:***

The visual awareness systems were considered more urgent than the aural systems. Within the passthrough approaches (*PA, PAR, PTAR, FPP*), the greater amount of reality incorporated the more urgent the approach was said to be (e.g. *PA* was not considered particularly urgent whereas *FPP* was). *TN* was the second most urgent condition which participants attributed to its unavoidable nature. 2 significant differences were found: between *FPP* and *DA* and between *FPP* and *RAA*.

5.1.4 ***Natural:***

All conditions, except for *TN*, were said to be natural methods of increasing awareness. Participants said *TN* was not natural because, relative to the others, it was more artificial, *P12: "the others just add reality into the VR scene whereas text is just this*

Presence Questions	*(0) Baseline*	*(1) Text Notification (TN)*	*(2) Photoreal Avatar (PA)*	*(3) Passthrough AR (PAR)*	*(4) Passthrough Transparent AR (PTAR)*	*(5) Full Passthrough + Pause (FPP)*	*(6) Dynamic* Audio (DA)	*(7) Remove All Audio (RAA)*	***Friedman Test***	***Wilcoxon Post-hoc*** *(p<0.0018)*
IPQ: Sense of Being There	5.81 (1.07)	5.62 (0.99)	5.62 (1.11)	4.94 (1.34)	5.06 (1.34)	4.50 (1.58)	5.69 (1.26)	5.69 (0.98)	$\chi^2(7) = 13.03$, *p=0.07*	N/A
IPQ: Involvement	5.66 (1.09)	5.30 (1.14)	4.73 (1.14)	3.30 (1.34)	2.83 (0.69)	3.44 (1.55)	3.78 (0.94)	4.12 (0.91)	$\chi^2(7) = 55.54$, *p<0.0018*	0-3, 0-4, 0-5, 0-6, 0-7 1-4, 1-5, 1-6, 2-4, 2-5
Togetherness in Same Space	1.56 (0.86)	2.25 (1.56)	4.31 (1.83)	5.38 (1.86)	5.56 (1.86)	5.62 (1.87)	5.06 (1.39)	4.94 (1.78)	$\chi^2(7) = 51.32$, *p<0.0018*	0-2, 0-3, 0-4, 0-5, 0-6 0-7, 1-3, 1-4, 1-5, 1-6

Table 3: Mean (standard deviation) values, and significant differences, for our sense of presence / togetherness questions. A heatmap on the mean (standard deviation) ranges from white (lowest) to purple (highest) based on the scale of the measure. Note - for IPQ: Involvement the mean of the 4 statements of this subset of the IPQ questionnaire is reported.

Condition / Ranking	*1st*	*2nd*	*3rd*	*4th*	*5th*	*6th*	*7th*	*Average Ranking*
Dynamic Audio (DA)	5	1	3	6	0	0	1	2.94
Passthrough AR (PAR)	2	4	4	2	2	1	1	3.31
Photoreal Avatar (PA)	1	4	5	0	4	2	0	3.50
Passthrough Transparent AR (PTAR)	4	2	2	2	2	3	1	3.56
Remove All Audio (RAA)	1	5	1	2	5	2	0	3.69
Text Notification (TN)	3	0	1	1	1	4	6	5.06
Full Passthrough + Pause (FPP)	0	0	0	3	2	4	7	5.94

Table 4: The average ranking score (of a possible 7.0) for our awareness systems. The heatmap on average ranking ranges from white (lowest average) to purple (highest average) based on the scale of the measure. Of note are *TN* and *FPP* which ranked lowest yet were frequently used in the *Assessing Awareness Needs* evaluation.

abstract pop-up”. Only 1 significant difference was found: between *TN* and *DA*, the least (*TN*) and most (*DA*) natural conditions.

5.1.5 ***Easy To Understand:*** All approaches were considered easy to understand and no significant differences were found between any of the conditions. This is a positive result indicating our participants understood the awareness systems and reinforces the results of our think aloud exercise where we assessed their usage of them.

5.1.6 ***Informative:*** All approaches were considered informative and no significant differences were found between any of the conditions. Generally, the passthrough approaches (*PA, PAR, PTAR, FPP*) were considered more informative than the others which was expected due to the type of information about the bystander and surrounding area relayed.

5.1.7 ***Improved Communication:*** All of the approaches, apart from *TN*, were said to improve communication with a bystander. Generally, for the visual approaches, the more reality incorporated into the virtual environment the more effective the system was said to be at improving communication. Both aural approaches were also considered effective for improving communication. 4 significant differences were found: between *TN* and *PTAR, FPP, DA, RAA*.

5.1.8 ***Too Aware of the Real World:*** *TN, PA, DA* and *RAA* were not said to make participants too aware of the real world whereas *PAR, PTAR* and *FPP* were. 3 significant differences were found: between *TN* and *FPP*, between *PA* and *PTAR* and between *PA* and *FPP*.

5.2 Sense of Presence Evaluation Results

For *IPQ: Sense of Being There*, all conditions scored similarly with no significant differences being between them (Table 3). For *IPQ: Involvement*, 10 significant differences were found between the conditions. These were differences between: the baseline and *PAR, PTAR, FPP, DA, RAA*, between *TN* and *PTAR, FPP, DA*, and between *PA* and *PTAR, FPP*. Generally, *IPQ: Involvement* decreased as increasing amounts of reality were augmented into the virtual environment. Noteworthy is there was no significant difference between the baseline and *TN*, meaning despite being considered disruptive and frustrating in the usability evaluation that this did not significantly impact presence in VR. For *Togetherness in the Same Space*, all of the awareness systems, apart from *TN*, were said to increase feelings of togetherness and 10 significant differences were found between the conditions. These were significant differences between: the baseline and *PA, PAR, PTAR, FPP, DA, RAA* and between *TN* and *PAR, PTAR, FPP, DA*.

5.3 Preference Ranking Results

A Friedman test ($\chi^2(6) = 24.08$, *p<0.0024*) indicated significant differences between participants’ preferred awareness systems. A Wilcoxon Signed Rank test, with Bonferroni corrected p-values

Scenario	Description	Related Work
PAIR SCENARIOS - Where the same interaction occurs inside/outside the play area		
OUTSIDE-TV	A bystander, outside the play area, who ignores the VR user whilst watching TV *(#2 steps)*	[41, 52]
INSIDE-TV	A bystander, inside the play area, who ignores the VR user whilst watching TV *(#3 steps)*	[41, 52]
OUTSIDE-PHONE	A bystander, outside the play area, who ignores the VR user whilst using their smartphone *(#2 steps)*	[41, 52]
INSIDE-PHONE	A bystander, inside the play area, who ignores the VR user whilst using their smartphone *(#3 steps)*	[41, 52]
OUTSIDE-SHORT-VERBAL	A bystander, outside the play area, who verbally interacts with the VR user *(#2 steps)*	[40, 41]
INSIDE-SHORT-VERBAL	A bystander, inside the play area, who verbally interacts with the VR user *(#3 steps)*	[40, 41]
OUTSIDE-LONG-VERBAL	A bystander, outside the play area, who first ignores the VR user then verbally interacts with them *(#4 steps)*	[35, 40, 41, 52]
INSIDE-LONG-VERBAL	A bystander, inside the play area, who first ignores the VR user then verbally interacts with them *(#5 steps)*	[35, 40, 41, 52]
ACTION SCENARIOS - Where bystanders enact specific actions related to or near the bystander		
DUSTING-BYSTANDER	A bystander, inside the play area, who is moving and interacting with objects a lot *(#3 steps)*	[7, 41]
SILENT-OBSERVER	A bystander, outside the play area, silently watching the VR user *(#2 steps)*	[41]
FILMING-BYSTANDER	A bystander, outside the play area, filming the VR user with their smartphone without permission *(#2 steps)*	[41]
OTHER TYPES OF BYSTANDER SCENARIOS - Where the bystander isn't a single, known person		
DOG-BYSTANDER	A bystander with a pet enters the room *(#2 steps)*	[35, 41]
MULTIPLE-BYSTANDERS	Multiple bystanders enter the room *(#2 steps)*	[4, 35, 41]
UNRECOGNISED-BYSTANDER	The bystander who enters the room is not recognised by the VR user *(#2 steps)*	[38, 39]

Table 5: A summary of the interaction scenarios used in the *Assessing Awareness Needs* evaluation. The steps associated with each scenario are provided in full in the results section (Section 7).

($p<0.0024$), found 4 significant differences between: *FPP* and *PA, PAR, DA*, and *RAA*. These were significant differences between the least preferred approach (*FPP*) and both aural approaches (*DA* and *RAA*), and the two most preferred visual approaches (*PA* and *PAR*).

The average ranking score is shown in Table 4 (where a lower average ranking score indicates a higher preference towards an approach). *DA* performed best (2.94 out of 7.00) and was the 1st choice of 31.25% of participants. *TN* (5.06 out of 7.00) and *FPP* (5.94 out of 7.00) performed worst, in-line with their results in the other evaluation factors. When justifying their rankings, 9 participants said they wanted to balance increased awareness with retained immersion/presence wanting to *P5: "know someone is there but also still play the game"*, 4 prioritised awareness over immersion/presence believing it was *P9: "more important to be aware someone was there [than to play the game"* and 3 prioritised immersion/presence stating it was *P2: "important [to] know someone is there for safety reasons"*.

5.4 Baseline Usability Evaluation Discussion

The results of the *Baseline Usability* evaluation validate that our chosen awareness systems represent a breadth of degrees of awareness and presence, and so would enable participants to consider how these might be used to vary desired awareness based on a considered interaction scenario. In terms of usability, *DA, PA, PAR* performed well and scored highest in participants rankings. *TN*, meanwhile, performed poorly - being considered the second most frustrating/disruptive approach, the least natural, tied least informative, was not said to improve communication and ranked second lowest in participants rankings. Therefore, if users determine awareness choices based on the usability of the awareness system, from the results of our *Baseline Usability* evaluation, we would expect awareness to predominantly be provided by *DA, PA, PAR* and for participants to avoid *TN* which performed significantly worse.

6 ASSESSING AWARENESS NEEDS: STUDY DESIGN

While the *Baseline Usability* evaluation investigated the usability of our awareness systems, this evaluation method is limited by focusing on an objective assessment of each awareness system's usability and impact on sense of presence. This, however, does not answer, given the many ways awareness can be increased, how, when, and why a VR user will opt to use one approach over another. Therefore the *Assessing Awareness Needs* evaluation was designed to follow the *Baseline Usability* evaluation to investigate, using a think aloud exercise, how, when, and why participants would use the awareness systems experienced to increase their awareness during 14 bystander-VR user interaction scenarios.

6.1 Research Objectives (RO)

We examined how the awareness needs of a VR user are influenced by:

- ***RO1 - Initial & Prolonged Contact:*** identifying awareness needs at the initial point of bystander contact, and how these needs evolve based on the demands of the engagement
- ***RO2 - Encroachment:*** whether bystander interactions occur inside or outside of the play area
- ***RO3 - Activity:*** the bystander's actions and degree of engagement with the VR user
- ***RO4 - Bystander Type:*** bystanders unrecognised by the user; multiple bystanders; and bystanders with pets

With *RO1 - Initial & Prolonged Contact*, we aimed to understand what VR users' awareness needs were at their initial point of bystander contact (e.g. when the bystander enters the room / is detected by the VR headset) and, crucially, if/how these awareness needs changed during an interaction. With *RO2 - Encroachment*, we aimed to understand how a bystander's position relative to the VR user influenced awareness needs. That is, would an interaction occurring inside of the VR user's play area elicit the same needs if it occurred outside of the play area. With *RO3 - Activity*, we aimed to understand what impact the bystander's actions and engagement with the VR user (e.g. ignoring the VR user, engaged in a prolonged verbal interaction, etc) had on awareness needs. Finally, with *RO4 - Bystander Type*, we aimed to obtain initial insights into how the needs identified in the other research questions might change as the "type" of bystander changed (e.g. interactions with bystanders who were not a "single, known individuals").

6.2 Experimental Task: Design of our Bystander-VR User Interaction Scenarios

To ensure the scenarios used in our evaluation were realistic, we derived 14 interaction scenarios from known, frequently occurring, real-world interactions between bystanders and VR users [4, 29, 40, 41]. Our interaction scenarios described co-existing, verbal/non-verbal interactions occurring inside/outside of the VR user's play area (the predominant types of interactions which occur in-the-wild [41]). 8 scenarios were pairs of verbal/non-verbal interactions inside/outside the VR user's play area to explore the influence of the interaction's position (inside/outside the play area) on awareness needs. 3 scenarios were unique interactions to explore bystander actions of interest, and 3 scenarios investigated interactions with bystanders beyond the context of *"a single, known bystander"* used in all other scenarios.

To investigate how awareness needs might vary over the course an interaction, each scenario consisted of a series of discrete steps where each step represented a change during the described interaction where a VR user might want to increase/decrease awareness of the bystander and/or real-world. The scenarios ranged in length from 2 to 5 steps. To avoid confusion surrounding whether the VR user was aware of a pre-existing bystander, all scenarios began with the same first step, *"A person enters the room"*. Scenarios involving interactions inside of the play area all used a consistent step signalling bystander entry into the play area, *"They enter the VR user's play area"*, which always proceeded the *"A person enters the room"* step. Table 5 summarises the interaction scenarios:

6.3 Captured Data

For each step of every interaction scenario participants were tasked with selecting their awareness preference from the awareness systems they experienced in the first part of the study (*TN, PA, PAR, PTAR, FPP, DA, RAA*), in addition to the options of *"No Awareness (NA)"*, if they did not want any awareness system, and *"Remove The Headset (RTH)"* if they wanted to take off the headset. Participants who selected *RTH* were given the option of *"Put The Headset Back On"* in subsequent steps, however, no participant selected this during the study. Participants could combine awareness options (e.g. select *PA* and *DA*) but if they selected multiple were required to rank them by priority. Participants were instructed to think aloud during the task and were probed by the experimenter when applicable. To ensure participants understood the task, the first 2 scenarios acted as a tutorial where the experimenter guided the participant through completing the scenarios (e.g. explaining the UI of the survey tool used to record their choices, prompting them with questions to assist with the think aloud process). After this, the remaining 12 scenarios were presented in a randomised order.

6.4 Experimental Procedure: Assessing Awareness Needs Evaluation

Upon completing the *Baseline Usability* evaluation, after a short break, the *Assessing Awareness Needs* evaluation was explained and participants were told they would be presented with 14 step-by-step descriptions of bystander-VR user interactions. In these, participants were to imagine they were the VR user playing a game similar to the one they had just experienced in the study's first part. Participants were told the bystander, unless otherwise stated, was a known person to them (e.g. a friend they lived with) and the room in which the interaction occurred was similar in layout to the room they were currently in - one with open floor space for dedicated VR use but with furniture outside of the VR user's play area (e.g. a couch/TV). Participants were told their task was to select the amount of real world awareness they wanted to experience for each step of the described interactions, based on the aforementioned options. Participants were told they could select multiple awareness options for a given step but if they did they would be required to rank them by priority. It was stressed to participants throughout that they were free to choose *"no awareness"* whenever desired. Participants were instructed to think aloud during the task and told the experimenter would probe them with questions to explore comments they made in more detail or to prompt them if they were being too quiet. The study took on average 60 minutes to complete (approximately 30 minutes for each part). Upon completing the study participants were compensated for their time with a £10 Amazon voucher.

7 ASSESSING AWARENESS NEEDS EVALUATION: RESULTS

Analysis: We quantitatively analysed responses to each scenario (analysing each modality separately) by first calculating an average awareness score for every step of every scenario. We assigned each awareness option a rank ordered by the extent to which it increased awareness. For the aural awareness this was: *NA: 1, DA: 2, RAA: 3.* For the visual awareness this was: *NA: 1, TN: 2, PA: 3, PAR: 4, PTAR: 5, FPP: 6, TOH: 7.* This ranking was then used to calculate, for each step of every scenario, the mean and standard deviation awareness scores (Tables 6, 7, 9). Where applicable, a Friedman test was used to find significant differences between factors (steps within interaction scenarios) and pairwise comparisons using Wilcoxon Signed Rank tests. To further investigate how awareness needs changed, we calculated *"rate of change"* values to summarise, for each step of every scenario, the number of participants increasing, maintaining or decreasing awareness relative to the previous step's selected awareness options. For example, *(Visual Awareness - Increasing: 50.0%, Maintaining: 25.0%, Decreasing: 25.0%)* meant, for the given step, 50% of participants increased awareness from the previous step, 25.0% maintained prior levels of awareness and 25.0% decreased awareness. We used our quantitative analysis to reinforce the results of an initial coding [3] of participants' comments made discussing their choice of awareness options and expectations for how, when and why to increase awareness. Participants' comments were assigned emergent codes over repeated cycles with the codes grouped using a thematic approach. A single coder performed the coding (2 cycles) and reviewed the coding with 2 other researchers.

7.1 VR User Awareness Needs at the Initial Point of Bystander Contact/Detection (RO1)

To investigate the initial point of bystander contact, we used a consistent first step for all 14 interaction scenarios: *"A person enters the room"*. Participants consistently selected the same awareness option(s) for all occurrences of this step. That is, a participant's selected option(s) for this step in the first scenario was the same as their selection in the last. We hypothesized participants may, after being exposed to range of possible bystander-VR user interactions, change their awareness preferences for this step during the task, however, this did not occur as participants did not deviate from their initial choice.

Participants prioritised increasing visual awareness at the initial point of bystander contact: 9 participants increased only visual awareness, 2 only aural awareness and 2 both aural and visual awareness. 3 participants did not increase any awareness stating they did not consider bystander entry to justify it, *P1: "I don't really care if they enter the room or not"*. Examining the mean, standard deviation and rate of change values for this step (*Aural Awareness: M=1.25, SD=0.43, Increasing=25.0%, Maintaining=75.0%, Decreasing=N/A* and *Visual Awareness: M=2.25, SD=1.15, Increasing=68.75%, Maintaining=31.25%, Decreasing=N/A*) reinforces participants prioritised visual awareness and shows they wanted lower levels of awareness at this step.

Examining the chosen awareness option(s), for aural awareness, all 4 participants chose *DA* believing it was most appropriate, *P2: "it still gives you some immersion"*. For visual awareness, 9 participants selected less intrusive approaches (*TN: 5, PA: 4*) believing they were sufficient as initial increases of awareness, *P3: "It tells you someone's there and who they are"*. 2 participants selected the passthrough AR approaches (*PAR:* 1, *PTAR:* 1) wanting awareness of their surrounding environment, *P4: "I want to see what they are doing inside of the room as well"*. All participants who increased visual awareness but did not select *TN* said they wanted to know the bystander's position relative to their own.

Finding 1: Most VR users wanted to be informed visually of bystander existence at the initial point of contact/detection, ranging from text notifications to variations of passthrough views.

7.2 How VR User Awareness Needs Varied After Initial Bystander Contact/Detection (RO1)

After completing the study's second task, participants were asked to reflect on how they expected awareness to be provided throughout bystander-VR user interactions. These comments, combined with the experimenter's observation notes of how participants selected awareness options and the quantitative data of their choices, were used to create a categorisation of attitudes for how bystander awareness should be increased. This resulted in 4 personas outlining how participants, generally, expected bystander awareness to be provided:

(1) Incrementally Adjust Awareness: 6 participants wanted to initially increase awareness to a starting point and then for awareness to incrementally adjust contextually throughout the interaction. For example, if the participant selected *PA* when the bystander entered the room, if the bystander entered the play area then awareness would increase to *DA* and *PAR*. Participants believed this behaviour was the best compromise compromise for increasing awareness whilst retaining immersion in VR and was the least disruptive approach to providing awareness, *P4: "It gives you the right mix... gradually adjusts to the right balance"*.

(2) Sudden Alterations to Prioritise Awareness or Experience in VR: 6 participants wanted to initially increase awareness as minimally as possible and then contextually prioritise low/high awareness states throughout the interaction. For example, participants selected *TN* when the bystander entered the room but if the bystander entered the play area would increase awareness to *FPP*. Similarly, participants wanted decreases of awareness to be comparably sudden (e.g. decreasing from *FPP* to *TN*). Participants wanted this behaviour as they believed sharp changes in awareness was the best approach for focusing attention on what was most contextually important - the VR experience or bystander, *P16: "I want to prioritise and switch the extremes - either the VR experience or awareness of the person"*.

(3) Minimally Increase Visual Awareness, Rely Primarily on Aural Awareness: 2 participants wanted to initially increase only aural awareness and avoid increasing visual awareness unless absolutely necessary. Participants wanted this as they believed increasing aural awareness was sufficient for providing baseline levels of awareness throughout most interactions and because they considered the visual awareness systems highly disruptive, *P2: "[dynamic audio] tells me someone is there, that's all I want most of the time, give me something visual when safety is a concern"*.

(4) Prioritise Immersion: 2 participants wanted to increase awareness as infrequently as possible. These participants felt the goal of VR was to create as immersive an experience as possible and so should not disrupt the user unless absolutely necessary, *P1: "I don't really care if they enter the room or not"*.

Finding 2: We identified 4 personas for how bystander awareness should be provided. These were: (1) incrementally alter awareness contextually from a starting point, (2) use sudden changes in provided awareness to prioritise focus contextually on the bystander or VR experience, (3) predominantly increase aural awareness, minimally increase visual awareness, and (4) prioritise immersion in VR.

7.2.1 *VR Users' Motivation for Changing Awareness Needs:*

While the above personas outline how bystanders expected awareness to be provided (RO1), our task was designed to also investigate how several bystander characteristics (RO2-4) motivated a change in desired levels of bystander awareness. The subsequent subsections explore these characteristics in-depth, and can be summarised as how awareness needs of a VR user are influenced by:

- The bystander's position relative to the VR user (RO2, Section 7.3)
- The bystander's actions and engagement with the VR user (RO3, Section 7.4)

- The type of bystander with whom the VR user is interacting (RO4, Section 7.5)

7.3 The Influence of a Bystander's Position on a VR User's Awareness Needs (RO2)

7.3.1 ***Awareness Needs When a Bystander Enters the VR User's Play Area:*** To investigate the point of bystander entry into the VR user's play area we used a consistent step, *"They enter the VR user's play area"*, in all 5 scenarios involving an interaction inside of the play area. Participants consistently selected the same awareness option(s) for all occurrences of this step. Again, we hypothesized participants may change awareness preferences for this step as the task progressed, however, this was not found to occur.

Upon bystander entry into the play area, most participants increased their visual and/or aural awareness. The mean, standard deviation and rate of change values for the *"enters play area"* step, compared to the *"enters room"* step, highlight this and are summarised below:

- ***"A person enters the room:"***
  - *Aural Awareness: M=1.25, SD=0.43, Increasing=25.0%, Maintaining=75.0%, Decreasing=N/A*
  - *Visual Awareness: M=2.25, SD=1.15, Increasing=68.75%, Maintaining=31.25%, Decreasing=N/A*

- ***"They enter the play area:"***
  - *Aural Awareness: M=1.69, SD=0.85, Increasing=25.0%, Maintaining=68.75%, Decreasing=6.25%*
  - *Visual Awareness: M=3.88, SD=1.58, Increasing=75.0%, Maintaining=18.75%, Decreasing=6.25%*

As participants responses to the *"enters room"* and *"enters play area"* steps were consistent across all applicable scenarios, a statistical test was performed to test for significant differences between the steps for both modalities. For aural awareness, a Wilcoxon Signed Rank test (sufficient as there is only one comparison) reported no significant difference between the participants response to the *"A person enters the room"* and *"They enter the play area"* steps ($p>0.45$). For visual awareness, a Wilcoxon Signed Rank test (sufficient as there is only one comparison) reported a significant difference between participants response to the *"A person enters the room"* and *"They enter the play area"* steps ($p<0.05$).

Participants justified their perceived need to increase awareness, in particular visually, by stating its importance to prevent accidental collisions with the bystander, *P11: "VR needs to be safe, seeing their [the bystander's] position ensures you have the best chance of avoiding collisions"*. This importance of visually signalling a bystander's entry into the play area is further reinforced by participants selection of awareness option(s). 14 participants selected to trigger a visual awareness system when the bystander entered the play area *(TN: 1, PA: 3, PAR: 4, PTAR: 3, FPP: 3)*, 13 of which selected an approach which continuously relayed the bystander's position relative to the VR user.

The 3 participants who increased awareness but did not select an approach which relayed continuous positional information *(TN: 1, DA only: 2)* said they wanted notification of entry into the play area but trusted the bystander to prevent accidents from occurring, *P1 : "I want a heads up they're in it [the play area] but I trust them to keep their distance"*. Finally, 1 participant did not want any increased awareness upon bystander entry into the play area stating they did not consider this alone justification for increasing awareness.

> **Finding 3:** Most VR users wanted to increase visual awareness upon bystander entry into play area, where the bystander's position is continuously relayed relative to their own.

7.3.2 ***Awareness Needs for the Same Interaction Inside and Outside the VR User's Play Area.*** We included 4 pairs of scenarios to investigate the same bystander-VR user interaction occurring inside and outside of the play area (Table 6). Comparing the responses shows participants wanted higher levels of awareness (both aurally and visually) during interactions inside of the play area. 14 participants justified this by stating they had safety concerns when the bystander was located inside of the VR user's play area, *P9: "it feels more risky to have someone inside the play area, even if they are just sitting over there I'd still likely take the headset off to say 'what are you doing in here, I might hit you'"*. 8 participants also said they perceived an interaction inside of the play area to be more urgent than the same interaction outside of it, *P9: "it just feels more pressing when they've come into the play area to talk to you"*.

All interactions inside of the play area reported higher levels of desired awareness than the corresponding outside pair. The mean, standard deviation and rate of change values for all pairs of interaction scenarios are summarised in Table 6. The difference between the pairs is most prominent in desired visual awareness. For example, the *"They sit down and start using their phone"* step of the *OUTSIDE/INSIDE-PHONE* scenarios: *OUTSIDE-PHONE* scored *(Visual Awareness: M=1.25, SD=0.56, Increasing=6.25%, Maintaining=37.50%, Decreasing=56.25%)* while *INSIDE-PHONE* scored *(Visual Awareness: M=3.31, SD=2.17, Increasing=31.25%, Maintaining=18.75%, Decreasing=50.00%)*. Similar differences are seen for all pairs of scenarios in Table 6. Greater levels of desired awareness are also shown in participants choice of awareness option(s) across the scenarios (Table 8) where, for the inside scenarios, participants less frequently opted for no awareness and more frequently selected visual approaches which incorporated greater amounts of reality into the VR scene (e.g. *PAR, PTAR, FPP*).

> **Finding 4:** Interactions inside of the VR user's play area elicit greater awareness needs than the same interaction outside the play area. Interactions inside the play area were considered more dangerous and urgent than the same interaction outside of it.

7.4 The Influence of a Bystander's Actions on a VR User's Awareness Needs (RO3)

7.4.1 ***Awareness Needs For Interacting Bystanders:*** During scenarios involving interacting bystanders (e.g. bystanders who verbally interact with the VR user, *OUTSIDE-SHORT-VERBAL, INSIDE-SHORT-VERBAL, OUTSIDE-LONG-VERBAL, INSIDE-LONG-VERBAL*) participants attempted to prioritise the awareness modality which best fit the on-going interaction. That is, during verbal exchanges

Scenario	Steps	Mean	SD	% Increase	% Maintain	% Decrease
AURAL AWARENESS						
OUTSIDE-TV	*A person enters the room*:	1.25	0.43	25.00	75.00	0.00
	They sit down and turn on the TV:	1.19	0.53	12.50	62.50	25.00
	Mean:	1.22	0.48	18.75	68.75	25.00
INSIDE-TV	*A person enters the room*:	1.25	0.43	25.00	75.00	0.00
	They enter the VR user's play area:	1.69	0.85	25.00	68.75	6.25
	They sit down and turn on the TV:	1.69	0.92	18.75	62.50	18.75
	Mean:	1.54	0.76	22.92	68.75	12.50
OUTSIDE-PHONE	*A person enters the room*:	1.25	0.43	25.00	75.00	0.00
	They sit down and start using their phone:	1.13	0.33	6.25	75.00	18.75
	Mean:	1.19	0.39	15.63	75.00	18.75
INSIDE-PHONE	*A person enters the room*:	1.25	0.43	25.00	75.00	0.00
	They enter the VR user's play area:	1.69	0.85	25.00	68.75	6.25
	They sit down and start using their phone:	1.56	0.86	12.50	62.50	25.00
	Mean:	1.50	0.74	20.83	68.75	15.63
OUTSIDE-SHORT-VERBAL	*A person enters the room*:	1.25	0.43	25.00	75.00	0.00
	They verbally interact with the VR user (e.g. say they are going for lunch):	2.13	0.48	68.75	31.25	0.00
	Mean:	1.69	0.46	46.87	53.13	0.00
INSIDE-SHORT-VERBAL	*A person enters the room*:	1.25	0.43	25.00	75.00	0.00
	They enter the VR user's play area:	1.69	0.85	25.00	68.75	6.25
	They verbally interact with the VR user (e.g. say they are going for lunch):	2.31	0.58	56.25	43.75	0.00
	Mean:	1.75	0.64	35.42	62.50	3.13
OUTSIDE-LONG-VERBAL	*A person enters the room*:	1.25	0.43	25.00	75.00	0.00
	They sit down and start using their phone:	1.13	0.48	6.25	68.75	25.00
	After a few minutes they verbally interact with the VR user (e.g. ask about their VR experience):	2.19	0.53	87.50	6.25	6.25
	The VR user (you) respond to them:	2.44	0.61	25.00	75.00	0.00
	Mean:	1.75	0.51	35.94	56.25	10.42
INSIDE-LONG-VERBAL	*A person enters the room*:	1.25	0.43	25.00	75.00	0.00
	They enter the VR user's play area:	1.69	0.85	25.00	68.75	6.25
	They sit down and start using their phone:	1.56	0.79	6.25	68.75	25.00
	After a few minutes they verbally interact with the VR user (e.g. ask about their VR experience):	2.25	0.56	68.75	31.25	0.00
	The VR user (you) respond to them:	2.38	0.70	18.75	75.00	6.25
	Mean:	1.83	0.68	28.75	63.75	9.38
VISUAL AWARENESS						
OUTSIDE-TV	*A person enters the room*:	2.25	1.15	68.75	31.25	0.00
	They sit down and turn on the TV:	1.75	1.60	18.75	25.00	56.25
	Mean:	2.00	1.39	43.74	28.13	56.25
INSIDE-TV	*A person enters the room*:	2.25	1.15	68.75	31.25	0.00
	They enter the VR user's play area:	3.88	1.58	75.00	18.75	6.25
	They sit down and turn on the TV:	3.69	2.39	37.50	18.75	43.75
	Mean:	3.27	1.78	60.42	22.92	25.00
OUTSIDE-PHONE	*A person enters the room*:	2.25	1.15	68.75	31.25	0.00
	They sit down and start using their phone:	1.25	0.56	6.25	37.50	56.25
	Mean:	1.75	0.90	37.50	34.38	56.25
INSIDE-PHONE	*A person enters the room*:	2.25	1.15	68.75	31.25	0.00
	They enter the VR user's play area:	3.88	1.58	75.00	18.75	6.25
	They sit down and start using their phone:	3.31	2.17	31.25	18.75	50.00
	Mean:	3.15	1.68	58.33	22.93	28.13
OUTSIDE-SHORT-VERBAL	*A person enters the room*:	2.25	1.15	68.75	31.25	0.00
	They verbally interact with the VR user (e.g. say they are going for lunch):	2.44	1.90	18.75	43.75	37.50
	Mean:	2.34	1.57	43.75	37.50	37.50
INSIDE-SHORT-VERBAL	*A person enters the room*:	2.25	1.15	68.75	31.25	0.00
	They enter the VR user's play area:	3.88	1.58	75.00	18.75	6.25
	They verbally interact with the VR user (e.g. say they are going for lunch):	3.44	2.42	18.75	37.50	43.75
	Mean:	3.19	1.80	54.17	29.17	25.00
OUTSIDE-LONG-VERBAL	*A person enters the room*:	2.25	1.15	68.75	31.25	0.00
	They sit down and start using their phone:	1.63	1.27	12.50	43.75	43.75
	After a few minutes they verbally interact with the VR user (e.g. ask about their VR experience):	1.81	1.70	18.75	50.00	31.25
	The VR user (you) respond to them:	2.44	2.29	12.50	81.25	6.25
	Mean:	2.03	1.66	28.13	51.56	27.08
INSIDE-LONG-VERBAL	*A person enters the room*:	2.25	1.15	68.75	31.25	0.00
	They enter the VR user's play area:	3.88	1.58	75.00	18.75	6.25
	They sit down and start using their phone:	3.19	2.16	25.00	25.00	50.00
	After a few minutes they verbally interact with the VR user (e.g. ask about their VR experience):	3.25	2.41	12.50	68.75	18.75
	The VR user (you) respond to them:	3.88	2.52	12.50	81.25	6.25
	Mean:	3.29	2.03	38.75	45.00	20.31

Table 6: The mean, standard deviation, and rate of change values for the *PAIR SCENARIOS*. Heatmaps range from white (lowest) to purple/green/grey/red (highest) based on the scale of the measure. Each main row contains 1 interaction scenario, reporting the values of each step of the scenario. Results show greater awareness needs for the same interaction occurring inside the play area, opposed to outside of it, and a spike in aural awareness during verbal bystander-VR user interactions.

Scenario	Steps	Mean	SD	% Increase	% Maintain	% Decrease
AURAL AWARENESS						
DUSTING-BYSTANDER	*A person enters the room:*	1.25	0.43	25.00	75.00	0.00
	They enter the VR user's play area:	1.69	0.85	25.00	68.75	6.25
	They do a task which involves moving around the play area (e.g. dusting):	2.38	0.93	43.75	56.25	0.00
	Mean:	1.77	0.77	31.25	66.67	3.13
SILENT-OBSERVER	*A person enters the room:*	1.25	0.43	25.00	75.00	0.00
	They pause and watch the VR user:	1.19	0.39	0.00	93.75	6.25
	Mean:	1.22	0.41	12.50	84.38	6.25
FILMING-BYSTANDER	*A person enters the room:*	1.25	0.43	25.00	75.00	0.00
	They start to film the VR user using their smartphone:	1.81	0.95	37.50	50.00	12.50
	Mean:	1.53	0.74	31.25	62.50	12.50
VISUAL AWARENESS						
DUSTING-BYSTANDER	*A person enters the room:*	2.25	1.15	68.75	31.25	0.00
	They enter the VR user's play area:	3.88	1.58	75.00	18.75	6.25
	They do a task which involves moving around the play area (e.g. dusting):	5.75	1.60	75.00	18.75	6.25
	Mean:	3.96	1.46	72.92	22.91	6.25
SILENT-OBSERVER	*A person enters the room:*	2.25	1.15	68.75	31.25	0.00
	They pause and watch the VR user:	2.44	1.37	25.00	50.00	25.00
	Mean:	2.34	1.26	46.87	40.62	25.00
FILMING-BYSTANDER	*A person enters the room:*	2.25	1.15	68.75	31.25	0.00
	They start to film the VR user using their smartphone:	4.63	2.06	75.00	18.75	6.25
	Mean:	3.44	1.67	71.87	25.00	6.25

Table 7: The mean, standard deviation, and rate of change values for the *ACTION SCENARIOS*. Heatmaps on the mean and rate of changes range from white (lowest) to purple/green/grey/red (highest) based on the scale of the measure. Each main row contains 1 interaction scenario and reports the values of each step of the scenario. The results show a spike in awareness during high activity scenarios (*DUSTING-BYSTANDER*) and if the VR user's feels privacy is being encroached (*FILMING-BYSTANDER*).

Condition	% of Selected Steps (Inside Pairs)	% of Selected Steps (Outside Pairs)
AURAL AWARENESS		
No Awareness	53.13	58.75
Dynamic Audio (DA)	25.89	30.63
Remove All Audio (RAA)	20.98	10.63
VISUAL AWARENESS		
No Awareness	28.57	55.00
Text Notification (TN)	13.39	17.50
Photoreal Avatar (PA)	18.30	13.75
Passthrough AR (PAR)	10.71	4.38
Passthrough Transparent AR (PTAR)	11.61	5.00
Full Passthrough + Pause (FPP)	9.82	1.25
Take Off Headset (TOH)	7.59	3.13

Table 8: The frequency of chosen awareness options, relative to the number of possible steps, for the *PAIR SCENARIOS*. Heatmaps range from white (lowest) to purple (highest) based on the frequency. The results show greater visual awareness needs during interactions inside of the play area.

with the bystander they prioritised increasing aural awareness but prioritised visual awareness when not verbally interacting with them (Table 6).

During verbal exchanges, 15 participants said aural awareness should be increased and prioritised, *P10: "in the speaking interactions, audio awareness gets priority because that's the most important part"*. 1 participant disagreed stating, for our proposed scenarios, shouting over the in-VR audio would suffice. Attitudes towards visual awareness, during verbal exchanges, were more varied. 6 participants felt visual awareness was unnecessary, *P1 : "I don't need visual information just hear the content [verbal interaction]"*. 5 said it was essential to see the bystander's facial expressions and body language, *P8: "I want to see how they are reacting to what I'm saying"*. 5 said they wanted balanced levels of visual and aural awareness so felt some increased visual awareness was appropriate.

All participants said a longer verbal exchange would increase their desired visual awareness (and likelihood they would switch to a full view of reality), *P8: "the longer it goes on [the verbal exchange] the more I'd be likely to just exit VR until its over"*. Finally, all participants acknowledged if the conversation topic was serious, or the bystander requested it, they would remove the VR headset.

Finding 5: VR users will attempt to match the modalities of the interaction and increased awareness, and will prioritise increasing the awareness modality that best fits the modality of the interaction.

7.4.2 *Awareness Needs For Non-Interacting Bystanders:*

Participants desired varying levels of awareness around non-interacting bystanders depending on the bystander's actions in the surrounding environment. For example, participants were willing to decrease, or even remove all, awareness provided they felt safe and were not interacting with the bystander - as demonstrated by their response to the *OUTSIDE-PHONE* and *OUTSIDE-TV* scenarios (Table 6) where 13 participants felt comfortable maintaining or reducing bystander awareness, *P4: "If they are parked there [sitting outside the play area] and ignoring me then I don't need awareness until they do something else"*.

However, participants said an active bystander (e.g. one with a lot of movement around and interaction with the surrounding environment) justified higher levels of bystander awareness. This difference

Scenario	Steps	Mean	SD	% Increase	% Maintain	% Decrease
	AURAL AWARENESS					
BYSTANDER-DOG	*A person enters the room:*	1.25	0.43	25.00	75.00	0.00
	They have a dog:	1.69	0.92	31.25	56.25	12.50
	Mean:	1.47	0.72	28.12	65.63	12.50
MULTIPLE-BYSTANDERS	*A person enters the room:*	1.25	0.43	25.00	75.00	0.00
	4 more people enter after them:	2.13	0.99	56.25	43.75	0.00
	Mean:	1.69	0.77	40.62	59.38	0.00
UNRECOGNISED-BYSTANDER	*A person enters the room:*	1.25	0.43	25.00	75.00	0.00
	You don't recognise them:	2.63	0.78	81.25	18.75	0.00
	Mean:	1.94	0.63	53.12	46.88	0.00
	VISUAL AWARENESS					
BYSTANDER-DOG	*A person enters the room:*	2.25	1.15	68.75	31.25	0.00
	They have a dog:	4.63	1.76	75.00	25.00	0.00
	Mean:	3.44	1.49	71.87	28.13	0.00
MULTIPLE-BYSTANDERS	*A person enters the room:*	2.25	1.15	68.75	31.25	0.00
	4 more people enter after them:	5.19	2.04	68.75	25.00	6.25
	Mean:	3.72	1.65	68.75	28.13	6.25
UNRECOGNISED-BYSTANDER	*A person enters the room:*	2.25	1.15	68.75	31.25	0.00
	You don't recognise them:	6.25	1.30	100.00	0.00	0.00
	Mean:	4.25	1.22	84.37	15.63	0.00

Table 9: The mean / standard deviation values and rate of change percentages for the *OTHER TYPES OF BYSTANDER SCENARIOS*. Heatmaps on the mean and rate of changes range from white (lowest) to purple/green/grey/red (highest) based on the scale of the measure. Each main row contains 1 interaction scenario and reports the values of each step of the scenario. The results show differing awareness needs than a comparable interaction with a single, known bystander.

can be seen by comparing the *INSIDE-PHONE & INSIDE-TV* scenarios with the *DUSTING-BYSTANDER* scenario. In *INSIDE-PHONE & INSIDE-TV*, participants wanted low aural awareness and moderate visual awareness (Table 6) while in *DUSTING-BYSTANDER* wanted high levels of both aural and visual awareness (Table 7). Participants attributed this difference in awareness needs to the increased risk to their safety due the bystander's actions, *P8: "they're moving around a lot, that's risky for me, I'll just take the headset off until they finish"*.

7.4.3 *Awareness Needs When Privacy Is Encroached Upon:*

Participants wanted increased awareness of a bystander encroaching on their privacy. This is shown by comparing the *SILENT-OBSERVER* and *FILMING-BYSTANDER* scenarios (Table 7). Both concern a single, known bystander outside of the play area but differ with *SILENT-OBSERVER* involving a bystander silently observing the VR user whereas *FILMING-BYSTANDER* involves a bystander filming the VR user without their consent. For *SILENT-OBSERVER*, participants wanted low levels of aural and visual awareness. Most were comfortable with low awareness levels as they did not consider the bystander a risk to their safety, although 3 participants did increase awareness due to discomfort being silently watched by the bystander, *P7: "it's a bit creepy if they are just staring at me"*. In contrast, for *FILMING-BYSTANDER*, participants wanted greater levels of aural and visual awareness and justified this need by stating their concerns with the unsolicited filming of their actions and appearance, *P6: "I'd want to know they were doing it so I could confront them about it"*.

Finding 6: In addition to increasing awareness of, and facilitating interactions with, a bystander, VR users want bystander awareness systems to protect their privacy by notifying them of privacy encroaching bystander actions.

7.5 The Influence of the Type of Bystander on a VR User's Awareness Needs (RO4)

The bystander with whom the VR user is interacting with was found to influence awareness needs. 3 scenarios (*DOG-BYSTANDER, MULTIPLE-BYSTANDERS, UNRECOGNISED-BYSTANDER*) were designed to explore this by investigating changes in desired awareness should the bystander differ from the *"single, known bystander"* used in all other scenarios. Table 9 summarises the mean, standard deviation and rate of change values for each scenario and highlights greater levels of desired awareness compared to a similar interactions with a single, known bystander (e.g. *SILENT-OBSERVER*).

For *DOG-BYSTANDER*, participants prioritised increasing visual awareness and justified this by stating its importance to ensure the safety of both the VR user and animal. Additionally, 5 participants who selected to switch to a full view of reality (*FPP:* 1, *TOH:* 4), expressed an interest in exiting VR to interact with the animal, *P5: "I'd take the headset off to say hello to the dog"*.

For *MULTIPLE-BYSTANDERS*, participants selected a moderate level of aural awareness and high level of visual awareness. 9 participants selected to switch to a full view of reality when multiple bystanders entered (*FPP:* 2, *TOH:* 7). All said this was necessary to ensure safety and because they did not feel comfortable continuing to use VR. 6 participants increased visual awareness but remained in VR (*TN: 2, PAR: 3, PTAR: 1*) believing this was sufficient until the interaction required more of them (e.g. a verbal exchange with the bystanders). 1 participant opted for no increased awareness stating provided any bystanders were outside of the play area then they were comfortable without awareness until attention was desired.

For *UNRECOGNISED-BYSTANDER*, participants selected high levels of both aural and visual awareness. 13 participants selected to switch to a full view of reality (*FPP:* 2, *TOH:* 11) to investigate who the bystander was. The 3 participants who opted not switch to reality instead increased only their visual awareness (*PA:* 1, *PAR:* 2) and justified this by stating their chosen approach relayed sufficient information to them.

Finding 7: Bystanders, beyond the archetypal type studied (a single, known person), elicit different awareness needs and have their own unique set of challenges associated with them.

8 LIMITATIONS

We used a lab study which was necessary for a controlled, repeatable examination of a breadth of awareness systems but limits our findings. Future work should evaluate the use of awareness systems in-situ, and longitudinally [41], across a broader range of potential interactions. Our approach also used a fixed perspective of the same starting action for every interaction which provided a structured method of evaluating interactions but is not a perfect replication of in-the-wild behaviours [4, 41]. Furthermore, our approach focused on a single usage context - use of a VR game in a home setting - yet prior works have established situational factors such as the interaction's location [39, 41] and type of VR application used [7, 38] influence a VR user's awareness needs. Future work should therefore investigate alternative usage contexts such as a workplace setting and productivity task, e.g. a bystander entering the office of a colleague who is working in VR [31]. While we expect some crossover in a VR user's awareness needs with our results, as bystander awareness remains a safety feature in all contexts [4, 41], a VR user's desired awareness may differ (e.g. wanting high levels of awareness when gaming but minimal/no awareness during productivity tasks). Finally, as a technical note, we used an Oculus/Meta Quest 2 headset to conduct the study which is equipped with a black and white passthrough view, but newer devices (e.g. the Meta Quest Pro) are equipped with a colour passthrough view, and future work could replicate our work to investigate what effect, if any, the technical characteristics (e.g. the resolution, display colour, etc) of the passthrough view has on VR user preferences.

9 DISCUSSION & FUTURE WORK

Our results show, for *RO1 - Initial & Prolonged Contact*, most VR users want to be informed visually of a bystander's existence at the initial point of bystander contact/detection, albeit with varying opinions of this is achieved (e.g. some preferring text notifications, others variations of passthrough views, etc). Crucially, our results demonstrate VR user awareness needs are dynamic and change relative to past levels of bystander awareness and the current interaction context. For *RO2 - Encroachment*, we report greater awareness needs for interactions occurring inside of a VR user's play area compared to the same interaction outside of it due to a perceived increased risk to safety. For *RO3 - Activity*, most VR users prioritised the awareness modality that best fit the current interaction (e.g. prioritising increased aural awareness during verbal exchanges). Finally, for *RO4 - Bystander Type*, we confirm each archetypal bystander type has their own respective awareness needs (e.g. awareness needs for a "single, known bystander" differ from those of an "unrecognised bystander" or "group of multiple bystanders"). We therefore conclude this paper by discussing the implications of these results on the design of future bystander awareness systems, and the shortcomings of evaluating bystander awareness systems using the *Baseline Usability* evaluation method alone.

9.1 Establishing the Need for Socially Intelligent Bystander Awareness

We identified 4 personas (Finding 2) which demonstrate empirically, for the first time, VR users expect awareness of bystanders to dynamically vary based on the demands of the interaction context. This confirms the theories put forth by prior works that VR users want awareness to dynamically adapt relative to their engagement with a co-presence [9, 29, 35]. Additionally, our results show no single solution can adequately support the awareness needs of VR users who balance a complex trade-off between awareness and immersion, individual priorities and concerns in relation to the bystander (e.g. physical safety, social interaction, privacy), and the influence of experiential (e.g. presence, usability) and contextual factors (e.g. relationship to bystander, proximity, bystander actions). In doing so, this develops our understanding of bystander awareness systems conceptually and motivates the need for ***socially intelligent bystander awareness systems*** to be developed that are no longer motivated predominantly by increasing VR user safety [8] but instead by facilitating cross-reality interactions between bystanders and VR users from the initial point of bystander contact to a prolonged interaction with them. This, in turn, represents an evolution in the technical sophistication of bystander awareness systems and is an advancement beyond the approaches proposed currently (e.g. detection a bystander is co-present [29] or within some distance of the VR user [38]). Instead, *socially intelligent bystander awareness systems* will require more advanced sensing capabilities, e.g. social signal processing techniques to recognise and act on social signals and behaviours of bystander/VR users [7, 49], or context awareness methods [1, 12] to identify where the VR user is located, what they are doing, and what their awareness needs are relative to any given social interaction they then have. While this is an advancement in the technical capabilities of consumer VR hardware, the rapid technical advances seen in these devices in recent years highlights that functionally VR headsets will be capable of understanding such contextual and social information (and more) in the near future [2, 37]. It is essential then the design of bystander awareness systems benefit from such advances and that *socially intelligent bystander awareness systems*, capable of assigning awareness priorities as the demands of the interaction require, are built.

9.2 What Drives Awareness: Critical Moments and Context

We identified 3 critical moments which elicit a significant change in a VR user's awareness needs: *(M1) the initial point of bystander contact* (Finding 1), *(M2) bystander entry into the VR user's play area* (Finding 3), and *(M3) a verbal exchange between the VR user and bystander* (Finding 5). These are emergent moments within bystander-VR user interactions which elicit a significant change in a VR user's awareness needs with respect to the desired degree of awareness provided, or even a switch in the prioritised awareness modality. Whilst we expect our proposed critical moments will be refined and expanded upon in future works, they nonetheless show how awareness systems can be used to address fundamentally different awareness problems and provide a promising method of evaluating the nuance of awareness systems design and usage.

For example, at *(M1) the initial point of bystander contact*, our results show a clear desire for visual awareness - verifying VR users want VR headsets to be equipped with awareness systems to notify them of bystander existence [35, 36] and the range of visual systems they are willing to increase awareness with. Similarly, at *(M2) bystander entry into the play area*, our results show a clear want for visual awareness of the bystander through an awareness system that continuously relay the bystander's position relative to the VR user - reinforcing the use of increased bystander awareness as a safety precaution [8].

Crucially, however, there exist critical moments which not only provoke a significant change in the desired degrees of awareness but also motivate a switch in prioritised awareness modality. This is demonstrated during *(M3) verbal bystander-VR user exchanges*, where VR users, who predominantly prioritised visual awareness as a safety precaution, switched to prioritise aural awareness as it "best fit the modality of the interaction". Furthermore, VR users who wanted visual awareness, alongside aural awareness, said they wanted it to enhance their communication with the bystander (e.g. to see facial expressions and body language whilst interacting). This moment then represents a fundamentally different awareness need - to facilitate the verbal interaction - opposed to the others (e.g. *M1* and *M2*) which foremost concern protecting the VR user's safety. This represents a functionally different purpose for the awareness system, where awareness needs are centred around how best to serve the interaction and enhance communication between the bystander and VR user. This presents its own unique set of challenges then for what it means to increase awareness and further motivates the need for *socially intelligent bystander awareness systems* capable of distinguishing, and switching, awareness priorities as the social demands of the interaction context require.

9.3 Where Existing Methodologies Fall Short

That VR users do not manage bystander awareness based solely on the usability of awareness systems is most clearly demonstrated by participants response to *TN* across the *Baseline Usability* and *Assessing Awareness Needs* evaluations. In the *Baseline Usability* evaluation, *TN* was the second most disruptive and frustrating, least natural and tied least informative awareness system that was not said to improve communication with a bystander and ranked second lowest in participant's preference ranking of awareness systems. However, in the *Assessing Awareness Needs* evaluation, *TN* was the second most frequently selected visual awareness system. Participants justified their selection of *TN* by stating it best fit their awareness needs and desired immersion relative to the on-going interaction with the bystander: *P15: "I preferred other approaches but they don't give me the level of awareness I want at this point in the interaction. When something more happens, they [the bystander] start talking to me, then I'd want the avatar or the passthrough, but a lot of the time a text notification is all I need. A quick heads up to keep me informed."*.

9.4 The Need for New Approaches to VR User–Bystander Interaction Research

The contradictions seen between our *Baseline Usability* and *Assessing Awareness Needs* results necessitate we reflect on the prevailing methodology of assessing bystander awareness systems in HCI research. A typical, well-replicated approach (e.g. [7, 9–11, 29, 32, 38, 50, 54]) will implement one or more novel awareness systems along with one or more appropriate contexts from the literature, and perform a within-subjects evaluation, demonstrating optimization in terms of validated measures around presence, workload, usability, awareness etc. These evaluations are predominantly tested for a singular bystander archetype (a single, known person) with varying proximity [38, 43, 50] in a lab context - most often exploring the moment a bystander enters the room and interrupts the VR user [7, 10, 11, 29, 38].

Based on our findings, such an approach may produce misleading and inaccurate recommendations (e.g. discounting *TN*). This is because there is no *holistic* consideration that awareness needs vary significantly based on the interaction context. Without such consideration, our findings undermine the ecological validity of such studies. We suggest then as a community, we (a) consider alternate evaluation methodologies that can take into account these *critical moments* in bystander interactions, and (b) place further priority on integrative works that enable effective cross-comparison of bystander awareness approaches.

Regarding alternative evaluation methodologies, our paper details a series of critical moments that should be considered in evaluations as outlined in Section 9.4. We suggest such critical moments be incorporated into evaluation scenarios (e.g. through in-situ evaluations, acted out bystander interactions, nested simulated realities [26–28]), or be assessed after-the-fact (e.g. think aloud approaches where participants reflect on the suitability of the proposed approach versus standardised baselines across these critical moments - replicating our *Assessing Awareness Needs* evaluation design). Whilst we expect our critical moments will be refined and expanded upon in the future, they are nonetheless a first promising step towards improving the ecological validity of such evaluations, and we encourage their usage in future work.

Regarding integrative research that supports cross-comparison of awareness systems, firstly, we open source our bystander task[2] and implementations of these baseline awareness approaches to enable and encourage replication. Consideration should also be given to how research in other XR specialisms has facilitated integrative works. In particular, Luca et al's *"Locomotion Vault"* [5] shows how

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[2] https://www.dropbox.com/s/qppxizs4v4uv4mh/Re-Evaluating-Project.zip?dl=0

a breadth of research solutions can be evaluated based on standardised measures, allowing contributions to be better placed in context against prior work - providing designers with a comprehensive, single resource to find appropriate solutions and identify gaps for future designs.

9.5 Collaborative Co-located Bystander-VR User Interactions

Finally, it is worth acknowledging that a bystander (an individual physically near a VR user but who cannot directly interact with their virtual environment) represents only a singular type of individual with whom a VR user might interact. Furthermore, while bystanders and VR user during an interaction may be significantly engaged (e.g. verbally communicating and physically touching each other [41]) many works have developed systems to enable an individual (e.g. a co-located VR user [43, 51], a co-located augmented/mixed reality user [6, 22, 23, 30], or a co-located non-HMD user [13, 14, 21]) to directly interact with and change a VR user's virtual environment in a collaborative cross-reality interaction. While many of a VR user's core awareness needs remain during such interactions (e.g. an awareness system to prevent accidental collisions [43] or to facilitate verbal interactions [40]), such systems designed to enable collaborative cross-reality interactions have their own unique challenges and expectations [13, 17, 47]. Consequentially, future work is needed to investigate this transition - from initial awareness of a bystander through an awareness system to an active collaborator in a cross-reality interaction - and to determine which awareness needs persist throughout the entire interaction, and which are context specific (e.g. only applicable/needed when the individual is a bystander, is a co-located AR collaborator, etc).

10 CONCLUSION

Through this paper, we have exposed the weaknesses of prior research into bystander awareness, validating the occurrence of critical moments that lead to a varying degree of bystander awareness being desired by VR users. In doing so, we demonstrated that VR users seek to exploit a range of bystander awareness systems, suggesting the need for new, more ecologically valid, approaches to the holistic evaluation and combination of bystander awareness systems. By outlining this challenge, we take the first steps towards the creation of what we term *socially intelligent bystander awareness* - fundamental if VR headsets are to optimally and safely operate in complex and dynamic everyday social environments.

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