Dynamic Awareness Techniques For VR User Interactions With Bystanders

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Abstract

Virtual reality (VR) headsets are often used in shared, social, settings. However, the occlusive nature of VR headsets introduce significant barriers to a user's awareness of, and interactions with, bystanders (individuals physically near the VR user but who cannot directly interact with the user's virtual environment). This thesis posits that VR headsets do not sufficiently support a user's interaction with bystanders. This thesis investigates how technology-mediated bystander awareness systems can support use of VR headsets by automatically increasing a user's awareness of, and facilitating an interaction with, bystanders.

Survey 1 & 2 and Experiment 1 explored this by first investigating how interactions occur between bystanders and VR users and what impediments are encountered during these interactions. Experiments 2, 3, and 4 then built on this work by investigating the design of technology-mediated bystander awareness systems designed to support these interactions. Experiment 2 explored the impact of withholding a bystander's identity and position when informing a VR user of a bystander's co-presence, finding some users will exit VR upon being notified of bystander co-presence if they perceive the information relayed to be insufficient for contextualising the bystander. Experiments 3 and 4 explored how the audio experienced by a VR user might be manipulated to increase aural awareness of reality and facilitate a verbal interaction. Experiments 3 and 4 found automatically decreasing the audio's volume or partially/fully removing audio components are effective audio manipulations to facilitate verbal bystander-VR user interactions.

Finally, Experiment 5, informed by the findings of all prior studies, investigated if/how a VR user's awareness needs vary during an interaction with a bystander. Its results demonstrate that no single bystander awareness system 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, and the influence of experiential and contextual factors.

Declaration

The research presented in this thesis is entirely the author's own work. Research in this thesis has been published at the following venues, using only the parts of these papers that are directly attributable to the author:

- The research in Chapter 3 has been published at PerDis 2020: O'Hagan, Joseph, Julie R. Williamson, and Mohamed Khamis. "Bystander Interruption of VR Users." Proceedings of the 9TH ACM International Symposium on Pervasive Displays. 2020. [1]
- The research in Chapter 4 has been published at ISMAR 2021: O'Hagan, Joseph, Julie R. Williamson, Mark McGill, and Mohamed Khamis. "Safety, Power Imbalances, Ethics and Proxy Sex: Surveying In-The-Wild Interactions Between VR Users and Bystanders." 2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR). IEEE, 2021. [2]
- The research in Chapter 5 has been published at PerDis 2020: O'Hagan, Joseph, and Julie R. Williamson. "Reality Aware VR Headsets." Proceedings of the 9TH ACM International Symposium on Pervasive Displays. 2020. [3]
- The research in Chapter 6 (Experiment 3) has been published at PerDis 2020: O'Hagan, Joseph, and Julie R. Williamson. "Reality Aware VR Headsets." Proceedings of the 9TH ACM International Symposium on Pervasive Displays. 2020. [3]
- The research in Chapter 6 (Experiment 4) has been published at AVI 2022: O'Hagan, Joseph, Julie R. Williamson, Mohamed Khamis, and Mark McGill. "Exploring Manipulating In-VR Audio To Facilitate Verbal Interactions Between VR Users And Bystanders." Proceedings of the 2022 International Conference on Advanced Visual Interfaces. 2022. [4]
- The research in Chapter 7 (Experiment 5) has been published at CHI 2023: O'Hagan, Joseph, Julie R. Williamson, Florian Mathis, Mohamed Khamis, and Mark McGill. "Re-Evaluating VR User Awareness Needs During Bystander Interactions." Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems. 2023. [5]

And I set my heart to know wisdom and to know madness and folly. I perceived that this also is grasping for the wind. For in much wisdom is much grief, and he who increases knowledge increases sorrow.

- *Ecclesiastes 1:17-18*

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Chapter 1

Introduction

1.1 Motivation

Virtual reality (VR) is often used in shared, social, settings but interactions between VR users and bystanders (individuals physically near a VR user but who cannot directly interact with their virtual environment) remain problematic [6, 7]. YouTube [8], for example, hosts many *"VR fail videos"* showcasing examples of VR users accidentally colliding with bystanders [7] highlighting significant failures in a VR headset's ability to warn users when bystanders are nearby. Consider also the scenario where a bystander enters the surrounding environment of a VR user. Any awareness the VR user has of the bystander, assuming a well fit VR headset, is largely contingent upon them overhearing the bystander (e.g. their footsteps, speech, etc) above the immersive VR soundscape being experienced [9]. Consequentially, bystanders co-presence often goes unnoticed by VR users [10] creating a diminished social environment [6, 9] and risk to the VR user's safety [11, 7].

Central to this problem is the occlusive nature of VR which introduces significant barriers to a user's awareness of, and interaction with, bystanders [7, 9]. When experiencing VR, a user's visual, and often aural, senses and connection to their surrounding reality are overridden to create strong feelings of presence in the presented virtual environment [12, 13, 14]. However, the consequence of creating such immersive experiences is a reduced reality awareness [6, 3] that creates significant awareness shortcomings for a VR user, e.g. a lack of awareness: of co-present bystanders [6, 9], when near a wall or object [15], of peripheral objects [6], etc.

To overcome this, research and industry are increasingly examining the use of technology-mediated awareness systems to support the use of VR devices by automatically increasing a user's awareness of their surrounding reality [6]. For example, *boundary awareness systems* are included within commercial VR headsets to track a user's position within a designated safe area to use VR and will notify the user should they step too close to the area's boundary [16, 17, 18]. And increasingly efforts are being made to develop ***bystander awareness systems*** which support the use of VR by automatically increasing a VR user's awareness of, and facilitating an interaction with, bystanders [6, 9]. These bystander awareness systems are designed to create a bidirectional interaction between VR users and bystanders [6] by, for example, informing a VR user of co-present bystanders (e.g. using a text notification [19]), relaying the bystander's position to the VR user to prevent accidental collisions [20, 18], etc.

Yet, at present, surprisingly little is known about how bystander-VR user interactions occur and how they fail. Instead, bystander awareness systems are often designed and evaluated entirely within the lab with little or no empirical evidence of the interaction being designed for actually occurring between bystanders and VR users (e.g. [21, 20, 22, 23, 24]). Furthermore, with regards to the design of these bystander awareness systems, many open questions remain including: the impact of withholding information (e.g. the bystander's identity and position) from the VR user when notifying them of bystander co-presence, how verbal bystander-VR user interactions might be facilitated (e.g. by increasing a VR user's aural awareness), and how disparate works on bystander awareness might be brought together into cohesive systems to provide the *"right"* awareness to the VR user (i.e. how does a VR user's awareness needs vary based on the bystander's presence, proximity, actions, etc).

The research presented in this thesis investigated pertinent challenges regarding the design of these bystander awareness systems to increase a VR user's awareness of, and facilitate an interaction with, bystanders. Overall, this thesis aimed to provide contributions to develop our understanding of bystander awareness systems for VR users. This is achieved by first investigating how bystander-VR user interactions actually occur, identifying what impediments are experienced when interacting. Building on this understanding, it then investigated open questions regarding the design of bystander awareness systems. Specifically, it explored the impact of withholding information about a bystander's identity and position when notifying a VR user of bystander co-presence, and how a VR user's experienced audio might be manipulated to increase their aural awareness to facilitate a verbal bystander-VR user interaction. Finally, having investigated how bystander-VR user interactions occur and the design of bystander awareness systems, how a VR user's awareness needs might vary over the course of an interaction with a bystander is investigated to explore how disparate works on bystander awareness might be brought together into cohesive systems to contextually provide the *"right"* awareness to a VR user.

1.2 Thesis Statement

This thesis asserts VR headsets can better support interactions between VR users and bystanders through technology-mediated bystander awareness systems. This thesis presents new insights into how interactions between bystanders and VR users occur, identifying impediments encountered during these interactions. This thesis also presents the design and evaluation of bystander awareness systems to increase a VR user's awareness of, and facilitate an interruption with, a bystander. Finally, this thesis demonstrates that no single awareness technique can adequately support the awareness needs of VR users during an interaction with a bystander. Instead, a VR user's awareness needs are shown to be a complex trade-off between awareness and immersion, individual priorities and concerns in relation to the bystander, and the influence of experiential and contextual factors.

1.3 Research Questions

This thesis answers the following research questions:

- **RQ1:** When bystanders interrupt a VR user...
  - **1.1.** how do they enact interruptions?
  - **1.2.** what factors impact comfort and willingness to enact these interruptions?
- **RQ2:** When bystanders and VR users interact...
  - **2.1.** what is the context of the interaction?
  - **2.2.** what impediments are encountered when interacting?
- **RQ3:** When notifying a VR user of bystander co-presence what is the impact of withholding...
  - **3.1.** identifiable information about the bystander from the VR user?
  - **3.2.** the bystander's position from the VR user?
- **RQ4:** How may in-VR audio be manipulated to facilitate verbal bystander-VR user interactions?
- **RQ5:** When providing a VR user with increased bystander awareness...
  - **5.1.** what are critical moments when awareness techniques should change?
  - **5.2.** how do awareness needs change at critical moments?

1.4 Thesis Structure

This section briefly summarises the contents of each chapter.

Chapter 2 - Literature Review: presents a review of the literature and related work on the topics covered in this thesis. It begins by discussing the definitions for key terms such as *"virtual reality"*, *"immersion"*, and *"presence"* used by this thesis. It then covers impediments experienced by VR users due to interactions with their surrounding reality. Particular focus is given here to problems which occur when bystanders and VR users interact. After this, systems designed to support VR use by alleviating/mitigating impediments caused by reality are discussed. First, a summary of works investigating *boundary awareness systems* to ensure users can use VR safely within a space are summarised. Next, a summary of works investigating *object awareness systems* to ensure VR user safety but also alleviate usability issues are summarised. Finally, works investigating *bystander awareness systems* are discussed, with a particular focus on the gaps in the literature which this thesis addresses.

Chapter 3 - Bystander Interruption of VR Users: reports on Survey 1 and Experiment 1 which investigated how bystanders interrupt a VR user, their comfort when interrupting, and their willingness to use one interruption strategy over another. Survey 1 investigated bystander comfort and willingness to use a variety of possible interruption strategies when interrupting a known/unknown VR user in various private/public settings. Experiment 1 then investigated, in practice, how bystanders enact the interruption of a known VR user in a private setting to investigate the rationale behind chosen interruption strategies. This chapter contributes towards answering **RQ1**.

Chapter 4 - In-The-Wild Interactions Between Bystanders & VR Users: reports on Survey 2 which investigated how bystanders and VR users interact in-the-wild and what impediments they encounter when interacting. Survey 2 collected empirical evidence of in-the-wild bystander-VR user interactions and its results present an overview of how bystander-VR user interactions (including interruptions) occur and of the impediments encountered when bystanders and VR users interact, answering **RQ2**. Survey 2's results also reinforce the findings of Survey 1 and Experiment 1, all of which contribute to answering **RQ1**. Finally, the findings of Chapters 3 and 4 inform the design of Experiments 2, 3, 4, and 5 presented in the subsequent chapters of this thesis.

Chapter 5 - Bystander Awareness Systems Without Identifiable / Positional Information: reports on Experiment 2 which investigated the impact of withholding a bystander's identifiable information and position in the surrounding environment when notifying a VR user of bystander co-presence. Its results answer **RQ3** and inform the design of the bystander awareness systems used in Experiment 5 in Chapter 7.

Chapter 6 - Manipulation of In-VR Audio to Increase a VR User's Aural Awareness: reports on Experiments 3 and 4 which investigate methods of manipulating a VR user's experienced in-VR audio to increase their aural awareness of their surrounding environment. Experiment 3 investigated the effectiveness of, and attitudes towards, automatically decreasing/increasing a VR user's experienced in-VR audio volume to increase/decrease awareness of nearby sound events. Experiment 4 then built directly on the results of Experiment 3 and investigated the effectiveness of, and attitudes towards, automatically decreasing in-VR audio volume and partially/full removing in-VR audio to facilitate a verbal bystander-VR user interaction. The results of Experiments 3 and 4 answer **RQ4** and inform the design of the bystander awareness systems used in Experiment 5 in Chapter 7.

Chapter 7 - Awareness Needs During Bystander-VR User Interactions: reports on Experiment 5 which investigated how a VR user's awareness needs might vary during an interaction with a bystander. The design of Experiment 5 was informed by the findings of all prior chapters of this thesis and investigated how disparate approaches towards increasing a VR user's awareness of a bystander might be utilised in conjunction to contextually provide a VR user with optimal levels of bystander awareness and immersion in VR. The results of Experiment 5 answer **RQ5**.

Chapter 8 - Conclusions: summarises the research contained in the thesis and reflects on how it answered the Research Questions set out at its beginning. This chapter also summarises the main contributions that are made by the thesis, and discusses some of the limitations of the research and how this could be addressed in future work.

1.5 Overview of Studies

A summary of the studies presented in this thesis and the research questions each study/chapter contributes to answering is presented below in Table 1.1.

RQ	Chapter	Study	Purpose
RQ1	Chapter 3	Survey 1 Experiment 1	Investigate how bystanders interrupt VR users, and what factors influence bystanders when interrupting
	Chapter 4	Survey 2	Collect empirical evidence of in-the-wild bystander interruptions of VR users
RQ2	Chapter 4	Survey 2	Investigate how bystanders and VR users interact, and what impediments are experienced when interacting
			Collect empirical evidence of in-the-wild bystander interactions with VR users
RQ3	Chapter 5	Experiment 2	Investigate the impact of withholding identifiable and position information about the bystander when notifying a VR user of a bystander's co-presence
RQ4	Chapter 6	Experiment 3 Experiment 4	Investigate methods of manipulating in-VR audio to facilitate a verbal bystander-VR user interaction
RQ5	Chapter 7	Experiment 5	Investigate how contextual factors during a bystander-VR user interaction influence a VR user's awareness needs

Table 1.1: A summary of studies presented in this thesis and research question each study contributes towards answering

Chapter 2

Literature Review

2.1 Introduction

The opening chapter introduced the fundamental problem this thesis addresses: that there is a lack of research around how VR users and bystanders interact and the design/use of technology-mediate systems to support VR users during these interactions. This chapter reviews the existing literature relevant to addressing this problem.

It begins by discussing the concepts and definitions relevant to this work used throughout this thesis. It discusses the nature of this work relative to the topics of mixed reality, augmented reality, and virtual reality (Section 2.2). It then provides a definition for virtual reality (Section 2.3) and discusses the current state of consumer virtual reality technologies. After this, the concepts of *immersion* and *sense of presence* within a virtual environment are defined and discussed (Section 2.4). While these sections do not address any of the research questions directly they are imperative for contextualising the problems addressed by this thesis.

Following this, a discussion of the impediments experienced by a VR user because of the occlusive nature of VR headsets, and the user's reduced awareness of their surrounding reality, is provided (Section 2.5). A particular emphasis is put on the problems encountered when VR users interact with bystanders. This section provides the literature motivating the topic of this thesis, and discusses topics that are particularly relevant in motivating **Research Question 1** and **Research Question 2**.

The literature review then introduces *reality awareness systems* (Section 2.6) where an overview is given of how these technology-mediated awareness systems can support a user's use of VR. An overview of boundary awareness systems (Section 2.7) is then provided summarising works designed to ensure a VR user's physical safety when using a VR. After this, an overview of object awareness systems (Section 2.8) is provided to summarising works designed to increase VR user's awareness, and facilitate their use, of objects in their surrounding environment from within VR. Finally, an overview of bystander awareness systems (Section 2.9) is given which summarises existing systems proposed and discusses gaps in the existing literature. This motivates **Research Question 3**, **Research Question 4**, and **Research Question 5** of this thesis.

2.2 The Virtuality-Reality Continuum

This thesis discusses work related to the topics of virtual reality, mixed reality, and augmented reality. However, as noted by both Speicher et al [25] and Steuer [26], multiple definitions of these terms are available and accepted within the community and literature. Therefore it is necessary that this literature review begin by discussing the definitions used for the underlying concepts that this thesis builds upon.

This thesis uses Milgram's reality-virtuality continuum [27, 28] (Figure 2.1) to conceptualise the relationship between augmented, mixed, and virtual reality. Milgram's reality-virtuality continuum describes this relationship between the concepts of augmented, mixed, and virtual reality as a continuous scale ranging between the completely virtual, a virtuality, and the completely real, reality [27, 28] . This continuum encompasses all possible variations and compositions of real and virtual objects, therefore is a suitable model to be used throughout this thesis. From Milgram's continuum, a mixed reality (MR) display is defined as one which any point between reality and virtual reality on the reality-virtuality continuum [27, 28]. Additionally, from Milgram's continuum, definitions for augmented virtuality (AV) as a virtuality view that is augmented with elements of reality, and augmented reality (AR) as a reality view that is augmented with elements of virtuality are obtained [27, 28].

Depending on the amount of reality or virtuality augmented, a display/experience can inhabit significantly different position on this continuum. For example, a minor augmentation to reality (e.g. overlaying a virtual character onto a view of reality (Figure 2.2)) would place close to reality on the scale. Whereas a major augmentation (e.g. augmenting a photoreal avatar of bystander into a VR scene (Figure 2.2)) would place nearer to virtuality.

Finally, it is worth considering the placement of the works contained within this thesis on the virtuality-reality continuum. This thesis focuses primarily on VR systems (defined/discussed in Section 2.3) and the design of bystander awareness systems for VR users (discussed in Section 2.9). These bystander awareness systems are used by VR users to augment their experience in VR (their view of virtuality) with information about reality. This represents

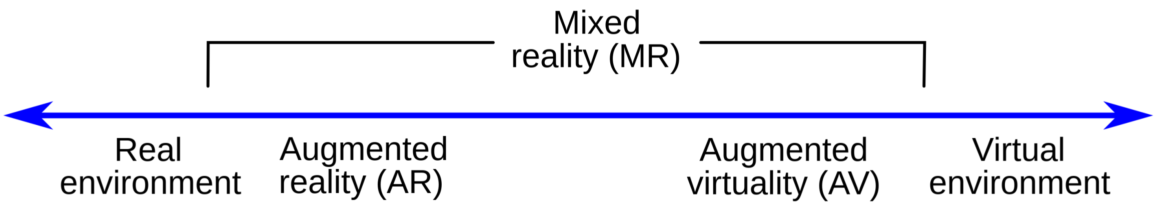


Figure 2.1: A visualisation of Migram's virtuality-reality continuum [27, 28], source: [29]

Figure 2.2: Left: Pokemon Go [30] is an example of a AR application that would place near the reality end of the virtuality-reality coninuum. Right McGill et al's *Dose of Reality* system [6] which would place near the virtuality end of the continuum.

a transition along the virtuality-reality continuum from a VR experience (full virtuality) towards, depending on the degree of reality augmented, an AV, AR or full view of reality. This thesis then investigates the design of bystander awareness systems which initiate a transition from a state of full virtuality towards reality to some point on the continuum.

2.3 Virtual Reality

As highlighted by Steuer, several definitions of virtual reality (VR) are available and used within the community [26]. Therefore, this literature review must establish a definition of VR to be used in this thesis. A suitable definition is: *"Virtual Reality is electronic simulations of environments experienced via head-mounted eye goggles and wired clothing enabling the end user to interact in realistic three-dimensional situations"* [26]. The key characteristics being a computer-simulated, multi-sensory environment (primarily visual/aural) in which a human experiences telepresence [14]. Essential also is that *"immersion"* and *"sense of presence"* within a VR are defined. These are provided in Section 2.4 while a brief summary of the current state of consumer VR technologies is provided below.

2.3.1 The Current State of Consumer VR Technologies

It is worth, briefly, highlighting the current state of consumer VR technologies to further assist with contextualising the works contained within this thesis. Current consumer VR headsets come in two form factors: tethered headsets (where the headset is powered by some additional hardware it is connected directly to via cable, e.g. PlayStation VR [31]) and standalone headsets (where the headset is an all-in-one, wireless device, e.g. Meta Quest 2 [32]). Most tethered and standalone VR headsets are capable of providing a user with both stationary experiences (where the VR user interacts with the presented virtual environment from a standing or seated position) [33], and room-scale experiences (where 360 degree tracking enables a user to walk freely around a defined *"play area"* and have their real-life motions/movement reflected directly within the presented virtual environment) [34]. Of these, stationary experiences are currently the most widespread amongst consumer VR applications [35, 36].

In terms of VR's applications, the predominant use of consumer VR technologies is, at present, entertainment purposes [37] primarily as a gaming device [33]. Finally, regarding where VR is currently used, the majority of VR use occurs within homes [36], although VR displays in public spaces (e.g. museums and art exhibitions [38]) are becoming increasingly common, and research has investigated the use of VR in a range of settings including the workplace [39], in transit [40], and in public spaces [41].

This overview is provided to contextualise the choice participant's tasks during the experiments reported in this thesis. This often is a VR user located in a private setting who is using VR for entertainment purposes. This context was chosen ensure ecological validity by evaluating investigated systems using a primary task which recreated the affordances of typical, current home VR usage.

2.4 Immersion and Sense of Presence in Virtual Reality

2.4.1 Defining Immersion and Sense of Presence in VR

Due to the varying definitions used within the literature, it necessary to establish the definitions of *"immersion"* and *"sense of presence"* in VR to be used throughout this thesis. This thesis uses Slater's conceptualisation of immersion and sense of presence in VR [12, 13] which are widely accepted and used throughout the literature [42].

Immersion, as conceptualised by Slater, is an objective assessment of a VR system which provides a quantifiable description of the capabilities of the technology and its ability to portray a reality [12, 13]. Immersion, under Slater's definition, is distinct from how the virtual environment experienced by the VR user is perceived [12]. Instead, Slater defines the user's subjective interpretation of and response to the portrayed reality as their sense of presence in the virtual environment [12]. Sense of presence, under Slater's definition, captures the user's subjective sensation of using the VR experience and is said to consist of *place illusion*, the *"sensation of being in a real place"* [43], and *plausibility illusion*, the *"illusion that the scenario being depicted is actually occurring"* [43].

2.4.2 Measuring a User's Immersion in VR

A number of approaches have been proposed within the literature of measuring a user's level of immersion in VR. As such, it is also necessary to discuss how immersion is measured within this thesis.

This thesis uses Slater's conceptualisation of immersion in VR [12, 13]. Under Slater's definition, immersion is an objective assessment of a VR system which provides a quantifiable description of the capabilities of the technology and its ability to present a VR experience to a user [12]. This provides an objective assessment and summation of a VR device's technical capabilities (e.g. its pixel density, resolution, maximum field of view, comfort being worn, etc [12]) of which various information databases are available online (e.g. [44]).

Therefore, as this thesis makes use of commercial VR headsets to perform its experimental work and because the focus of the experimental work is on the user's experience in VR and response to a presented bystander awareness system, capturing a measure of immersion is of less significance. As such, the immersion of the VR headsets used to conduct the experimental work in this thesis is not measured directly because such information is easily accessible already through online databases [44]).

2.4.3 Measuring a User's Sense of Presence in VR

A number of approaches have been proposed within the literature of measuring a user's sense of presence in VR. As such, it is also necessary to discuss how sense of presence is measured by the experiments included within this thesis.

A user's sense of presence can be measured in a multitude of ways including through brain activity and physiological measures [45] or more traditional questionnaire and/or qualitative methods [42]. While many studies often employ application-specific questions to measure presence, many generalised questionnaires exist also and are widely used in the literature (e.g. the Igroup Presence Questionnaire (IPQ) [46]). The use of these questionnaires is often wide ranged [47], for example, using the IPQ questionnaire to measure sense of presence in: a VR game [48], simulated reality experiences [49], mixed reality applications [6], etc. Mai et al, meanwhile, have argued such existing approaches fail to sufficiently capture *"breaks-in-presence"* [50] and proposed a post-experience technique where participants reflect on their sense of presence by drawing a line to visualise experienced presence over time. Slater et al also has argued that the current predominant evaluation methods are problematic and proposed a combination of psychological methods and qualitative methods would likely give a more accurate measure [12].

However, despite numerous opinions regarding how a VR user's sense of presence should be defined and measured, when a VR user is immersed and acts within in a virtual environment then it can be argued there is some sign of presence. Throughout this thesis, sense of presence in VR is measured using the IPQ questionnaire [46] because of its widespread acceptance and use throughout the literature, particularly in bystander awareness works most closely related to the topic of this thesis (e.g. [6, 21, 20], etc). Additionally, alongside the relevant IPQ questions, as also often occurs within the literature (e.g. [6, 21]), several application-specific presence questions are asked alongside qualitative, semi-open interview questions to further explore participant thoughts surrounding their sense of presence with an experience.

2.4.4 Factors Influencing Sense of Presence in VR

A user's sense of presence in VR is created by a multitude of factors [14, 43]. From a technical standpoint, the immersive capabilities of the device being used by the VR user can influence sense of presence through the pixel density, the maximum field of view, the quality of the head tracking, etc [12, 44]. From an experiential standpoint, sense of presence can be influenced the audio/visual content being experienced [51, 48], the interaction design of the experience [52, 53], the user's engagement in the experience [54], external distractions in the real-world surrounding environment [6], etc. Most significant of these for this thesis is the influence of external distractions disrupting the user's experience (discussed in detail in Section 2.5) and the experienced audio/visual content (discussed below).

The Influence of Experienced Visual Content on Sense of Presence

VR devices primarily create an immersive experience by overriding the visual and auditory senses of the user [6]. Of these, in a typical consumer VR experience [33, 35, 37], the visual feedback experienced by the user is likely the core focus of the user's attention and more prominent influence on the user's sense of presence [12, 13, 14]. Consequentially, any disruption to the virtual environments presented visuals risks significantly impacting the VR user's sense of presence [6].

For example, consider the scenario where a photoreal avatar of a bystander is augmented into a VR user's underwater cartoon virtual environment as a safety/awareness system [6, 55, 15]. The aesthetic mismatch between the real person and cartoon virtual environment, and the photoreal person breathing underwater without any apparatus break Slater's place and plausibility illusions, potentially reducing the user's sense of presence [43]. Furthermore, the addition of this content into the VR scene creates a persistent, focal point of attention/distraction for the VR user that also potentially reduces their sense of presence [6].

Such scenarios are of particular interest to this thesis because the typical approaches taken to increase a VR user's awareness of their surrounding environment (including bystanders) is to do so visually. In the topic of increasing bystander awareness (the subject of this thesis) prior works have gone as far as to suggest that VR users will choose to use the awareness system which minimally disrupt their sense of presence in VR [6, 55, 56]. However, such theories have not yet been verified experimentally and conceptually this approach to selecting awareness system preferences ignores additional factors such as the information content of an awareness system and an individual's preferences/priorities during interactions (discussed in detail in Section 2.9).

The Influence of Experienced Audio Content on Sense of Presence

Audio can serve many functions within an interactive experience [57]. For example, in (both VR and non-VR) video games audio can provide contextual information to the player [58], improve performance [59], and affect player behaviours (e.g. decrease/increase risk taking [60]), etc. One core function of audio, particularly relevant to VR, is to facilitate presence/enjoyment of an interactive experience [60, 61, 62, 51]. For example, audio perceived as unsuitable for an experience (e.g. out of place or thematically mismatched) can decrease a user's sense of presence, enjoyment, focus and performance [63, 64, 65].

Surprisingly, however, is that recent empirical work by Rogers et al has shown, using a commercial VR video game, the minimal effect of background music in creating a user's sense of presence in the experience [66]. While the older VR literature (e.g. late 1990s / early 2000s) strongly suggested ambient noises, sound effects and background music all increased immersion/presence in VR [67, 68] studies of *modern VR* (e.g. 2013 onward) have failed to replicate this [66, 60, 69, 70]. Instead, more recent works have indicated that audio may be less prominent in creating immersive VR experiences than was previously thought. Recent works have demonstrated how ambient noises, sound effects and background music experienced by a VR user can all be removed or manipulated without significantly altering their sense of presence [66, 60, 69, 70]. Therefore, while audio designed as a focal point of an experience can still play a significant role in immersion/presence [64, 63], the findings of recent work indicate that audio, not designed as the focal point of the VR experience, can be manipulated without altering the user's presence.

2.4.5 Summary

These works provide an overview of the concepts of immersion and sense of presence in VR that are relevant throughout this thesis. This section outlines how immersion and sense of presence can be measured, and discusses how they are measured in Experiments 2-5 presented in this thesis. This section also provides an overview of how visual/audio factors can influence a user's sense of presence in VR. Most significant is the discussion of recent works which have demonstrated that a VR user's experienced in-VR audio can be manipulated without influencing the user's sense of presence in VR. This work in-part motivates **Research Question 4** which investigates the application of this phenomenon of manipulating experienced in-VR audio, without significantly impacting sense of presence in VR, to increase a VR user's aural awareness of a bystander by asking:

- **RQ4:** How may in-VR audio be manipulated to facilitate verbal bystander-VR user interactions?

2.5 Impediments Using VR Due to Reduced Awareness of Reality

2.5.1 Reduced Awareness of Surrounding Reality

While the immersive experience provided by VR is the greatest strength of the technology it is also the technology's most significant weakness. As a user's visual, and often aural, senses are occluded by a VR experience in use, interactions with the user's surrounding reality can become problematic [9]. As a consequence of this reduced awareness of reality, as noted by McGill et al, *"even tasks as simple as picking up a cup become difficult without a visual reference"* [6].

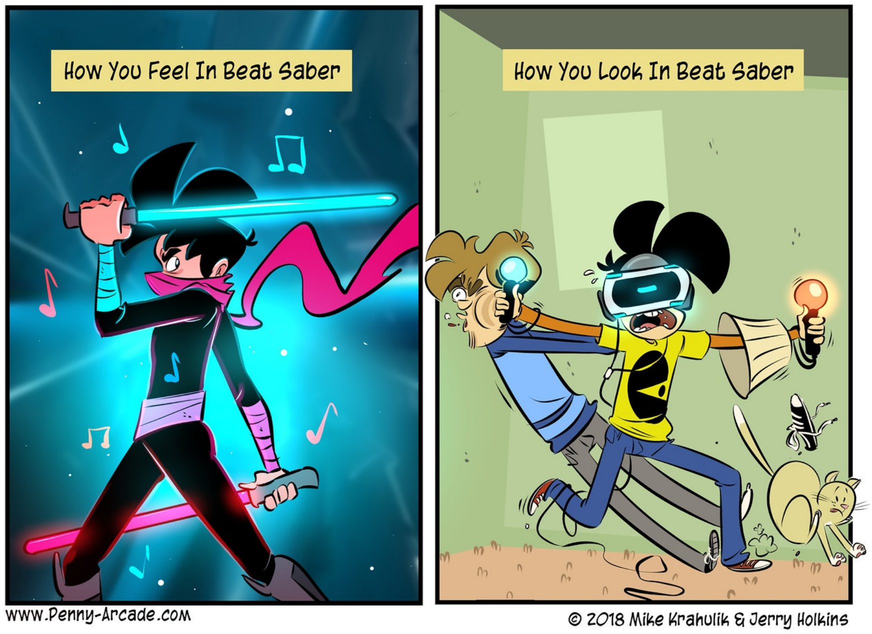


Figure 2.3: A comic strip illustrating the problematic nature of a VR user's interaction with their surrounding reality, source: [71]

Various works have directly investigated what impediments, with respect to the user's interaction with their surrounding reality, impact an individual's use and enjoyment of VR [6, 9, 72, 15]. McGill et al surveyed VR users to investigate the extent to which factors such as awareness of objects, bystanders, and the surrounding environment impeded individuals ability to use and enjoy VR [6]. McGill et al found VR users desire easier interactions with objects/persons in their surrounding environment and consider this a greater impediment to their use/enjoyment of VR than cybersickness [6, 73], concluding there was a pertinent need to develop awareness systems to relay information about objects/persons to a VR user.

Ghosh et al also surveyed VR users to explore attitudes towards common interactions with reality a user might experience (e.g. being *"close to a wall"*, if *"someone enters the room"*) [9]. Their results found that VR users were concerned due to their reduced awareness of their physical surroundings, in particular noting how the *"changing physical environment"* (e.g. the potential for the surroundings to change) was a significant concern of users. Meanwhile, I have previously, through a card sorting study, explored VR user attitudes towards increasing awareness generally (including awareness of bystanders, pets, objects, sounds, and digital notifications) while in VR [72]. This work found that users want VR headsets to be equipped with awareness systems to automatically increase a user's awareness of their surrounding physical reality, but also noted that VR users vary considerably in their expectations for how this increased awareness should be provided.

Generally, the primary impediments reported by the literature which are encountered by

VR users are caused by a lack of awareness of: the physical space VR is being used in, objects/peripherals, and co-located non-VR persons (bystanders). Whereas awareness of the physical space is primarily a safety concern (e.g. to prevent a VR user from colliding with a wall or furniture) [15], and awareness of objects/peripherals a usability issue (e.g. to enable effective VR use) [74], awareness of co-located non-VR persons (bystanders) is both a safety concern (e.g. as bystanders may exploit an unaware VR user [11]) and usability issue (e.g. as bystanders and VR users must often interact [7]). As the latter of these issues (awareness of bystanders) is the focus of this thesis it is necessary that the problematic nature of this, and works investigating these interactions, be discussed in more detail.

2.5.2 Problems Encountered When VR Users and Bystanders Interact

VR technology is often used in shared, social settings [7, 36], meaning that VR users and bystanders (co-located non-VR persons who cannot directly interact with the VR user's virtual environment) must sometimes interact [6, 75, 76]. As highlighted previously, the occlusive nature of VR technology can, due to a user's reduced awareness of their surrounding real-world environment, impede on a user's experience in VR and their interaction with reality. Interactions between bystanders and VR users are noted as being particularly problematic in this regard [6, 9, 72]. However, before discussing why such interactions are problematic it is beneficial to first contextualise these interactions by characterising the bystander in terms of their role and relationship to the VR user and highlighting the setting in which the interactions are taking place.

Who Are These Bystanders?

This thesis defines a bystander as *"an individual physically near a VR user who cannot directly interact with the VR user's virtual environment"*. This definition is derived from the perspective of the VR user, who is defined as an individual using a VR device. The defining characteristics of a bystander with this definition are: (a) being physical co-located to the VR user/device, and (b) being unable to directly interact with a VR user's VE. As such, bystanders may have a wide range of potential actions, e.g. observing what the VR user is doing, talking with the VR user, ignoring the VR user, temporarily navigating past the VR user, etc. Such a framing of the bystander is common in the literature (e.g. [6, 9, 22, 21, 52]). It is important to note also that this thesis only investigates non-XR bystanders, although AR or VR bystanders can exist [77, 78], e.g. a co-located person using AR or VR to observe a VR user's VE but who cannot directly interact with the observed VE.

Due to VR's use primarily within the home [7], bystander-VR user interactions predominantly occur in home environments. As such, most bystanders will be either a family member, friend, housemate, or partner of the VR user [7, 79]. This existing relationship between the VR user and bystander, and setting of interaction, brings with it a set of normative social behaviours that are expected and embedded within any interaction [79]. VR, like any technology [80], will need to account for such behaviours. For example, Rostami and McMillan studied VR stage productions involving VR users and bystanders and documented the necessity of creating strategies of monitoring, maintenance, and recovery from errors during an the ongoing performance [81] - methods of essentially "tuning" the VR device, experience, and use to the expectations of the usage context. Embedding VR use within the home will be no different as solutions will be needed to ensure its fit within the home [80]. Crucial will be how VR devices account for interactions with bystanders [6], interactions which, at present, remain problematic and impeded upon due to the barrier VR creates between a user and nearby persons [9, 6].

The Problematic Nature of Bystander-VR User Interactions

To highlight why bystander-VR user interactions are often problematic, consider, for example, when a bystander enters the surrounding environment of a VR user. Any awareness the VR user has of this bystander (assuming a well-fitting headset) is contingent upon them hearing real-world audio (e.g. footsteps, speech) over the existing immersive VR soundscape. Often, however, such awareness cues are missed [9, 76], leaving the VR user susceptible to the (potentially malicious [11]) actions of a bystander, at risk of accidentally colliding with a bystander [7], and unable to initiate an interaction with any bystander [6]. Even if aware of the bystander, problems remain including: difficulty effectively verbally communicating due to a VR user's reduced aural awareness [9], bystander uncertainty over whether it is appropriate to interact or not [10, 75], the continued risk of accidental collisions [7] or accidental encroachment by the VR user on the bystander's personal space [18].

However, despite the problematic nature of bystander-VR user interactions, research investigating how they occur and what impediments are encountered during them, is limited. At present, research has only investigated if bystanders can identify *"opportune moments"* to interrupt VR users [10], how to alleviate bystander uncertainty over whether a VR user wants to be interacted with [75, 82], and a classification of *"VR fail"* videos posted online [7]. The findings of these, and gaps within the literature, are discussed below.

Bystander Interruption of VR Users

George et al investigated, in a lab experiment, if bystanders can identify *"opportune moments"* (e.g. when the VR user was switching tasks or during low activity in-VR actions) to interrupt VR users [10]. Their results found bystanders could, with high levels of accuracy, identify such *"opportune moments"* to interrupt. They also reported that most bystanders opted to interrupt verbally although some chose to interrupt using physical contact or to interrupt verbally and then follow up with physical contact (e.g. saying "hello" then touching the VR user on the shoulder).

However, George et al's work is limited by the depth to which they investigated how bystanders interrupt VR users. Although George et al reported bystanders are willing to interrupt verbally and/or with physical contract, they did not investigate the rational behind a bystander's choice of interrupt approach, nor their comfort when interrupting. Additionally, they did not consider if bystanders want technical solutions to interrupt with (e.g. peripheral devices to trigger an interruption notification in the VR user's virtual environment which Williamson et al have found positive sentiment towards in a focus group study [76]). Nor did their methodology (which tasked how participants should interrupt) enable interruptions to occur as they might in practice (e.g. immediately upon entry into the room with little observation of the VR user's actions). Finally, George et al's work only considered a single type of bystander-VR user interaction, bystander interruption of VR users, leaving open questions as to what occurs after the interruption occurs (e.g. does the user exit VR to interact with the bystander, etc). Therefore, while George et al's work is insightful, their work leaves gaps within the literature that motivate: (a) a deeper investigation into how bystanders interrupt VR users - the rational behind chosen interruption strategies, and comfort when interrupting, and (b) a broader investigation of how bystander-VR user interactions occur empirically.

Bystander Uncertainty Whether to Interact With a VR User

George et al reported, in their work investigating if bystanders can identify *"opportune moments"* to interrupt VR users [10], that several participants disobeyed the experiment's instruction to interrupt a VR user. Instead, these participants waited until the VR user naturally removed the headset before interacting with them. When asked why they had not interrupted the VR user mid-task, their participants replied they were uncertain if the VR user would want to be interrupted while *"deeply engaged with another device"*.

Additional works in the literature [75, 82] have discussed similar sentiments to this, using them to justify the creation of systems to inform a bystander whether a VR user is open to being interrupted or not. Gottsacker et al. proposed attaching LEDs onto a VR headset as *"activity cues"* to act as status indicators to signal to a bystander whether a VR user wishes to be disturbed or not [82]. Mai et al. proposed *TransparentHMD* to create the illusion of a VR user having a face to encourage bystanders in initiate an interaction with them [75, 83]. Yet, while these solutions have been shown to effectively encourage bystanders to interact with VR users [75, 84, 82], the onus of initiating a bystander-VR user interaction remains entirely on the bystander. As such, the VR user remains uninformed of any potential bystander co-presence unless the bystander initiates an interaction with them, leaving many of the problematic impediments this creates unresolved.

The Breakdown of Bystander-VR User Interactions

Dao et al investigated how a broader range of bystander-VR user interactions occur in-the-wild by categorising *"VR fail videos"* posted online to understand why accidents, particularly with bystanders, occurred [7]. In their work they identified several *"failure types"* (e.g. accidental collisions with bystanders, tripping over the physical surroundings, etc), the causes of failure (e.g. fear, sensorimotor mismatch, excessive reactions), and bystander reactions to the failure (e.g. laughter, concern, supportive behaviours). However, while Dao et al's data set is valuable for further illustrating significant usability failures, their very nature - videos shared online for (at least in-part) entertainment purposes - introduces a selection bias in the available data (e.g. noteworthy, shocking, or entertaining incidents). Consequently, this may portray a more exaggerated and skewed picture of the everyday challenges encountered by VR users. Absent, due to the little entertainment value offered to a viewer, are videos of more grounded interactions which are not posted online.

Therefore, while Dao et al's work does provide empirical evidence of real-world *"VR fails"* occurring, there exists a gap in the literature where more empirical evidence and data is needed on the more mundane, real experiences and usability challenges faced when bystanders and VR users interact in-the-wild. Capturing this data will enhance our understanding of what and how interactions between VR users and bystanders actually occur, and provide a greater level of ecological validity when contrasted with other published data sets (e.g. Dao et al's *"VR fails"* [7]). This, in turn, will provide a better understanding of bystander-VR user interactions - how they occur, existing attitudes towards them, what impediments are encountered during them - an understanding of which can be used to design better approaches of supporting them using bystander awareness systems designed to increase a VR user's awareness of, and facilitate an interaction with, bystanders.

2.5.3 Summary

These works provide an overview of the impediments experienced by VR users due to their diminished awareness of their surrounding environment when using a VR headset, with a particular focus on discussing the problematic nature of a VR user's interaction with bystanders. Additionally, this section discusses the existing works investigating interactions between VR users and bystanders, highlighting a gap in the literature and need to better understand how these interactions occur and what problems are experienced during them. This work motivates **Research Question 1** and **Research Question 2** which investigate how bystanders interrupt VR users (**RQ1**) and the context of bystander-VR user interactions (**RQ2**):

- **RQ1:** When bystanders interrupt a VR user...
  - **1.1.** how do they enact interruptions?
  - **1.2.** what factors impact comfort and willingness to enact these interruptions?
- **RQ2:** When bystanders and VR users interact...
  - **2.1.** what is the context of the interaction?
  - **2.2.** what impediments are encountered when interacting?

2.6 Alleviating Reality Impediments Through Increased Reality Awareness

Drawing inspiration from context aware technologies [85, 86], research and industry have increasingly examined technology-mediated cross-reality awareness systems, referred to as *reality awareness systems*, to support the use of VR devices. These systems are designed to alleviate the impediments created by the occlusive nature of VR by automatically increasing a VR user's awareness of, and facilitating an interaction with, their surrounding reality. Typically, these systems work by identifying some element of a VR user's surrounding reality and then increasing their awareness of it or facilitating an interaction with it [6].

Many examples of reality awareness systems have been presented within the literature. These include awareness systems to increase a VR user's awareness of: walls [16, 18], chairs [16], peripherals devices [74], food/drink [6], bystanders (both human and animal) [6, 17], etc. Of these, the three most prominent high level categories of reality awareness system are:

- ***Boundary Awareness Systems:*** to provide a VR user with awareness of the physical space in which they are using VR (e.g. to prevent accidental collisions with walls/furniture/etc)
- ***Object Awareness Systems:*** to provide a VR user awareness of objects/peripherals (e.g. to facilitate the use of the objects whilst in VR)
- ***Bystander Awareness Systems:*** to provide a VR user awareness of bystanders (e.g. to increase awareness of, and facilitate interactions with, co-located, non-VR persons)

The remaining sections of this literature review summarises relevant works on each of these high level awareness system categories.

2.7 Boundary Awareness Systems

2.7.1 The Role of Boundary Awareness Systems

When using VR a user is at risk of accidentally colliding with walls [16], objects [7], people [7, 87], etc. To reduce this risk, and increase user safety, VR headsets (particularly those capable of room-scale VR [34]) typically require the user define a safe *"play area"* to use VR in [16] (Figure 2.4). To ensure the user stays within this designated space a *boundary awareness system* is often used to notify the user when they near the edge of their defined safe area. These systems work by tracking the VR user's position relative to the edges of the defined space and contextually notifying the user if they near the edges.

2.7.2 Predominant Approaches to Boundary Awareness Systems

The obvious benefit of boundary awareness systems to VR users has resulted in much research investigating how VR users can be effectively notified when they near the edge of a defined play area. For example, text notification have been proposed [88] as well as the appearance of virtual walls within the VR scene [18]. Haptic and audio alerts [15, 89, 90] have also been investigated as a method of maximising preserved immersion/presence in VR. However, these were significantly less effective at protecting users than visual feedback systems [15]. As such, the initial approach taken to implement boundary awareness systems in consumer VR headsets (circa 2016) was to contextually display a virtual wall within the virtual environment if the VR user neared the edge of the play area [18, 91] (e.g. Figure 2.4).

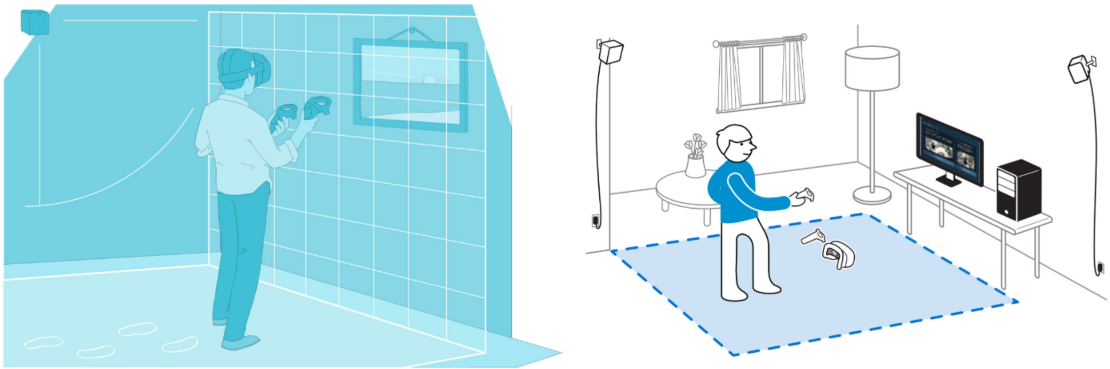


Figure 2.4: Illustrations of how the HTC Vive chaperone (boundary awareness system) presents the VR user with a virtual wall when near the edge of their defined “play area” [91]. Left: an illustration of the virtual wall feedback. Right: an illustration of a VR user who has defined a “play area” within their physical reality to use VR within.

Research, meanwhile, as the technical capabilities of VR headsets advanced began to explore alternative boundary awareness systems designs. Utilising the depth cameras of VR headsets [78], approaches were proposed to contextually switch a VR user’s view from virtuality to passthrough-reality [92] when near the edge of their defined play area, or to augment outlines of reality within the virtual environment when near in proximity to the VR user [93]. Furthermore, the effectiveness of these methods for increasing awareness has led to the integration of variations of both approaches within current consumer headsets (e.g. passthrough views [17] and the space sense with the Quest line of headsets [17]).

However, these passthrough-based approaches (e.g. switching from virtuality to a full view of reality), while effective at helping the user navigate their physical space, can be disruptive and disorienting [94]. Virtual walls, while less information rich, mitigate against such disruptions by preserving greater amounts of virtuality, and so are preferred by some VR users [72] and have motivated research into less visually intrusive solutions such as redirected walking techniques [95, 96, 97]. Furthermore, these differing user preferences highlight the need for VR headsets to equipped with a range of boundary awareness systems, each increasing awareness differently, and to allow users to use the approach which best fits their awareness/immersion needs.

2.8 Object Awareness Systems

2.8.1 Diminished Awareness of Objects

When using VR, due to their visual awareness being overwritten by the presented virtual content, a user's awareness of nearby objects is often impeded upon [6]. This, depending on the object, has a number of possible consequence for the VR user. For example, diminished awareness of larger objects (e.g. tables, chairs, lamps, etc) located inside or near a VR user's play area pose a safety risk to the user who might accidentally trip over or collide with the object [7, 72]. Meanwhile, smaller objects (e.g. food/drink [98], or un-augmented peripherals devices being used [6]) can create usability issues where the user is unable to effectively use the object due to their lack of awareness of it. As such, VR users often find themselves exiting VR, by either partially/fully removing the headset [6, 24] or switching to a passthrough view [92], to interact with objects in their surrounding environment.

2.8.2 Increased Awareness of Peripheral Devices

To reduce the reliance on exiting a VR experience a number of solutions have been proposed by researchers to increase a VR user's awareness of nearby objects. For peripheral devices (e.g. devices used to control the VR experience in use) the approach adopted by VR hardware manufacturers has been track any device being used and augment a virtual equivalent of it within user's virtual environment [99, 100]. This enables a user to locate any in use peripheral device in real-time from within the virtual environment. Furthermore, to preserve presence in VR, often these tracked controller model are replaced are made to fit within an application in use (e.g. replacing the controller model with a gun in a shooting game, Figure 2.5).

Figure 2.5: *Space Pirate Trainer* [101] a game in which the VR controllers are replaced with models of guns that are held/used by users within the game.

While, this approach has also been proposed for augmenting keyboards into a virtual environment [102], McGill et al investigated augmenting a photoreal view of the actual keyboard and user's hands into the virtual environment [6]. Much work has subsequently built on these two approaches by, for example, exploring various aesthetics to convey the user's hands over/using the keyboard [74, 103, 104, 105]. The results of these research efforts has been the commercial release of VR compatible keyboards onto the consumer market (e.g. [106]) which utilise the approach of tracking the keyboard and augmenting a virtual model into the VR user's virtual environment and supporting a variety of feedback methods to allow users to see their hands whilst using the keyboard [74].

2.8.3 Increased Awareness of General Objects

While systems to augment peripheral devices into a virtual environment can rely, to a degree, on built in sensors/tracking technology, systems to increase a user's awareness of general objects (e.g. food/drink, tables, chairs, etc) require a different approach. Within the literature, two of the most prominent methods of achieving this are: substitutional reality [107, 108], and contextual object inclusion [6, 55, 109].

Substitutional reality approaches attempt to achieve object awareness by overlaying virtuality onto the user's physical, surrounding environment [107, 108]. Using this approach, any object in the user's environment has a 1-to-1 mapping with a virtual counterpart inside the user's virtual environment. Often, this virtual counterpart will match thematically with the presented VR content (e.g. an augmented chair will be altered to fit with the decor of the VR scene) [107]. This is because, in addition to the increased awareness of the objects, substitutional reality techniques often attempt to enhance the VR user's immersion by utilising the user's surrounding environment as passive haptics [110] which add tangibility to virtual objects within the virtual environment [107].

In contrast, works proposing contextual object inclusion, primarily aim to increase awareness as a usability feature (e.g. to enable a VR user to easily drink their coffee [6, 98], to provide sufficient awareness of a chair [109, 93], etc). For example, McGill et al proposed a system which would recognise contextual actions of the VR user (e.g. reaching for a food item) and then augment a partial view of reality into the user's virtual environment [6]. Sakata et al, meanwhile, proposed superimposing 3D point clouds of objects into the VR user's virtual environment [109], while Huang et al investigated how depth sensing could be used to create a depth map of the VR user's surrounding environment which could contextually outline objects when the VR user was close to them [93].

This variety of solution to providing a VR user with awareness of objects is discussed to further illustrate the need for VR headset to be equipped with a variety of awareness systems due to the differing needs/preferences of users [37]. Where some users prefer substitutional reality methods, due to the attempt to minimise disruption in VR, others prefer more direct photoreal object inclusion because of its temporary, and often more effective, ability to facilitate an interaction [37, 108, 6, 55]. This highlights, as discussed for boundary awareness systems also (Section 2.7), that there likely is no single, *"one-size-fits-all"* [20] solution to increasing a VR user's awareness of reality and that VR headsets need to be equipped with a range of solutions which users can choose from to best fit their awareness/immersion needs.

2.9 Bystander Awareness Systems

2.9.1 Defining Bystander Awareness Systems

Section 2.5 summaries the impediments faced by VR users due to their reduced awareness of reality when using VR devices. In particular, it discusses the problems this reduced awareness creates with respect to a VR user's interaction with a bystander (a co-located person who cannot interact with a VR user's virtual environment). To overcome this, research and industry have increasingly investigated the design of technology-mediated ***bystander awareness systems*** that support a user's use of VR by automatically increasing a user's awareness of, and facilitating interactions with, bystanders [6].

While works have explored systems to encourage bystanders to interact with a VR user (e.g. Mai et al's *TransparentHMD* or Gottsacker et al's LED *"activity status"* cues [82]) these approaches are not considered bystander awareness systems as they do not increase a VR user's awareness of a co-presence. Similarly, works exploring the creation of novel systems to allow VR users to collaborate with co-present persons (e.g. Gugenheimer et al's *ShareVR* [111]) are not consider bystander awareness systems either, as the co-present individual is no longer a bystander rather has become a co-located user with the ability to directly influence the VR user's virtual environment.

The definition used throughout this thesis then is that a bystander awareness system is: a technology-mediated awareness system that supports a user's use of VR by automatically increasing a user's awareness of bystanders. The key characteristics of which are that it: (a) increases the VR user's awareness, and (b) that the co-present person is a bystander (a co-located person who cannot interact with the VR user's virtual environment).

The primary purpose of bystander awareness systems put forth by works in the literature is to inform a VR user when a bystander is co-present [6]. In doing this, such works attempt to create a more bidirectional bystander-VR user interaction by enabling the VR user (who is made aware of any co-presence) to initiate an interaction with a bystander [6, 22]. Such works also, depending on the degree of positional information about the bystander relayed, attempt to prevent accidental collisions occurring between the VR user and bystander by increasing the VR user's spatial awareness of persons around them [87].

2.9.2 The Use of Bystander Awareness Systems to Support Bystander-VR User Interactions

Before discussing the current state of bystander awareness systems research, it is worth highlighting, through example, how these systems might support bystander-VR user interactions. To do this, consider a bystander-VR user interaction that occurs in the home between housemates/family members, the most predominant type of such an interaction that currently occurs (and the framing used by the experimental work of this thesis).

Suppose the bystander enters the room and needs to interrupt the VR user to ask them a time sensitive question, e.g. *"What time did you put dinner on? When do I need to take food out of the oven?"*. Any awareness the VR user has of the bystander, assuming a well-fit headset, is contingent upon them hearing the real-world audio of the bystander's entrance (e.g. footsteps) over the VR soundscape. Suppose the bystander's entrance has gone unnoticed, meaning the onus lies entirely on the bystander to interrupt the VR user.

The bystander could attempt to verbally attract attention, but the VR user is wearing noise-cancelling headphones meaning even the bystander's shouts may go unnoticed. The bystander is also reluctant to shout as they have just managed to get a baby to fall asleep in a nearby room and do not wish to risk wakening them. Therefore, the bystander must rely on a physical interruption and to approach the VR user, whose application in use requires them to swing their arms forcefully and often suddenly move in unpredictable directions, creating a significant risk of an accidental collision occurring.

A VR headset equipped with bystander awareness systems could support such an interaction in a variety of ways. At its most basic, a bystander awareness system could be used to detect the bystander's existence and inform the VR user of their co-presence. This is enough to enable a bidirectional interruption to occur [6] where the VR user can now choose to interrupt the bystander. Such a notification of bystander existence could be done temporarily, e.g, through a discrete text notification [19], or continuously, e.g. through a persistent photoreal avatar [6]. The latter approach is also beneficial for avoiding an accidental collision between the VR user and bystander [87] should the bystander still require movement around/near the VR user, assuming the VR user continues to use VR and does not exit to interact with them.

Alternatively, a bystander awareness system might increase the VR user's aural awareness meaning the bystander could speak to the VR user without shouting. Such a system might work by detecting and amplifying the bystander's voice to the VR user to enable to bystander to speak without shouting while still allowing the VR user to hear what they say.

This example highlights the use of only a few possible bystander awareness systems to alleviate a bystander interrupting a VR user, but demonstrates the potential of these systems, generally, to support bystander-VR user interactions. These same awareness systems can be re-used across a range of possible bystander-VR user interactions, e.g. to increase aural awareness to facilitate verbal bystander-VR user exchanges of any duration. Furthermore, many other types of bystander awareness systems can be created, e.g. systems to allow bystanders to build virtual walls that section off areas of a VR user's play area as their own [18]. Yet, for all the potential benefits of these systems shown by prior works there remains unanswered questions regarding their design and use which the subsequent section of this literature review summarises.

2.9.3 The Current State of Bystander Awareness Systems Research

McGill et al were the first to investigate the design of a bystander awareness system [6]. McGill et al developed a system which would automatically notify a VR user of bystander's existence by contextually blending a photoreal avatar of the bystander into the VR scene [6]. 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, many works has investigated a range of approaches to relay a bystander's co-presence to a VR user. For example, research has investigated the design of: text notifications [9, 19], audio notifications [9], haptic notifications [9, 56], visual radars [23], HUD icons [20], and various avatar aesthetics ranging from anonymous designs [9, 22, 24] to variations of photoreal avatars [55, 21]. A typical, widely used, evaluation of these (e.g. [6, 21, 20, 9]) will implement one or more novel awareness systems along with systems along with one or more appropriate contexts from the literature, and perform a within-subjects evaluation to assess: (a) whether the built system achieves some level of desired increased awareness, and (b) what impact, if any, this has on the VR user's sense of presence. As a consequence of this, prior works have found a variety of awareness system designs which can successfully increase a VR user's awareness of bystander with varying degrees of disruption to their experienced sense of presence. However, overarching questions remain unanswered regarding the design and use of these awareness systems.

The Unknown Impact of Withholding a Identifiable/Spatial Information About a Bystander When Notifying Co-presence

To illustrate a gap in the literature concerning the overarching design of bystander awareness systems, consider the use of text notifications to notify a VR user of a co-presence. Text notifications have been demonstrated, depending on their placement within the VR scene [88], to be effective methods of increasing a VR user's awareness of a co-presence [19, 88]. However, the typical text notification, by design, is anonymous (containing no identifiable information about the bystander) and contains no spatial information about the co-presence. Yet, at present, it is unknown what impact a lack of identifiable or spatial information about a bystander has on a VR user's behaviour when they are notified of bystander existence.

If VR users are comfortable being notified of a bystander's existence without being told the bystander's identity or position in the surrounding environment, then researchers and designers are not required to consider the impact the absence of this information will have on a bystander awareness system design. If, however, VR users are made uncomfortable by the absence of either then more informative bystander awareness designs are required. For example, if VR users are uncomfortable being notified of bystander existence without identifiable information then an anonymous text notification and an anonymous avatar are both at risk of creating discomfort with VR users. Therefore, it is essential that this open question in the literature be addressed due to the potential implications its answer has for a designer of a bystander awareness system.

The Singular Purpose of Existing Bystander Awareness Systems Research

The bystander awareness systems discussed in Section 2.9.3 are primarily designed to inform a VR user that a bystander is co-present [6], and possibly where they are located in the surrounding environment to prevent a collision with them [87]. This, however, represents only a single type, and purpose, of increased bystander awareness - informing the VR user that someone is there - and does not fully encapsulate the potential awareness needs of a VR user's interaction with a bystander [112]. For example, prior works have identified that VR users desire an increased aural awareness of their surrounding reality [9, 72]. Yet, at present, no work has explored how this increased aural awareness might be increased. Addressing such open challenges is essential, however, as developing awareness systems to support a bystander-VR user interaction beyond simply notifying the VR user that someone is co-present, is a significant development that increases the scope of how these awareness systems are used, e.g. to fully support and facilitate a prolonged cross-reality bystander-VR user interaction opposed to a tool designed to assist in the initiation of an interaction.

The Unknown Nature of a VR User's Awareness Needs During an Interaction With a Bystander

While the prior works highlighted in Section 2.9.3 have established how individual, singular bystander awareness systems can successfully notify a VR user of bystander co-presence [6, 9, 20, 21, 22, 23], at present, there is a lack of 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 the evaluation methodologies used in prior works focusing on evaluating 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.

Crucially, then, while prior works have evaluated the usability and impact on presence 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 evaluation methodologies used in past works, despite outlining many ways in which a VR user's awareness of a bystander 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. As such, it unknown if/how a VR user's awareness needs vary during an interaction with a bystander. Therefore, it is essential this open question be addressed because, at present, the fundamental question of how a VR user will actually employ bystander awareness systems to increase their awareness remains unanswered. As such, it is unknown if a single awareness system will suffice for the entire duration of a bystander-VR user interaction or if awareness systems need to be developed that can dynamically adapt bystander awareness relative to the needs of an on-going bystander-VR user interaction.

2.9.4 Summary

This section provides an overview of the bystander awareness systems proposed in the literature: their positioned purpose, their design, and the methodologies used to evaluate them. From this, this section discusses three gaps in the literature concerning the overarching design and use of bystander awareness systems.

From a design standpoint, the unknown impact of withholding identifiable and positional information from the VR user when notifying them of bystander co-presence is discussed which motivates **Research Question 3**:

- **RQ3:** When notifying a VR user of bystander co-presence what is the impact of withholding...
  - **3.1.** identifiable information about the bystander from the VR user?
  - **3.2.** the bystander's position from the VR user?

From a design standpoint, the purpose of increasing awareness was discussed, which highlights existing works have primarily focused on the problem of informing a VR user that someone is there. As such they have not considered how other types of bystander awareness (e.g. increasing aural awareness to facilitate a verbal interaction) may be increased. This, combined with works discussed in Section 2.4, motivates **Research Question 4**:

- **RQ4:** How may in-VR audio be manipulated to facilitate verbal bystander-VR user interactions?

From a usage standpoint, the evaluation methodologies of works on bystander awareness was discussed which highlights that existing works 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 this, it is unknown how a VR user's awareness needs might vary during an interaction with a bystander. This gap in the literature motivates **Research Question 5**:

- **RQ5:** When providing a VR user with increased bystander awareness...
  - **5.1.** what are critical moments when awareness techniques should change?
  - **5.2.** how do awareness needs change at critical moments?

2.10 Summary of Literature Review

This chapter reviewed research on three topics: (1) virtual reality and factors impacting a user's sense of presence in VR, (2) the problems faced by VR users due to their decreased awareness of reality, and (3) the design of reality awareness systems to support the use of VR by increasing awareness of reality from within VR.

As discussed in Section 2.5 research investigating bystander-VR user interactions is limited, and so there is a need for research to explore how interactions between bystanders and VR users occur and what problems are encountered during these interactions. This research gap motivated the following research questions:

- **RQ1:** When bystanders interrupt a VR user...
  - **1.1.** how do they enact interruptions?
  - **1.2.** what factors impact comfort and willingness to enact these interruptions?

- **RQ2:** When bystanders and VR users interact...
  - **2.1.** what is the context of the interaction?
  - **2.2.** what impediments are encountered when interacting?

Sections 2.6 and 2.9 highlight that the problems that are encountered during bystander-VR user interactions can be alleviated by technology-mediated awareness systems. However, more research is needed into these systems, in particular with respect to their design and use. This research gap motivated the following research questions:

- **RQ3:** When notifying a VR user of bystander co-presence what is the impact of withholding...
  - **3.1.** identifiable information about the bystander from the VR user?
  - **3.2.** the bystander's position from the VR user?
- **RQ4:** How may in-VR audio be manipulated to facilitate verbal bystander-VR user interactions?
- **RQ5:** When providing a VR user with increased bystander awareness...
  - **5.1.** what are critical moments when awareness techniques should change?
  - **5.2.** how do awareness needs change at critical moments?

Chapter 3

Bystander Interruption of VR Users

3.1 Introduction

VR is often used in shared, social settings [7] but interactions between VR users and bystanders in these settings are not well understood [6, 9]. Consequentially, this lack of thorough understanding of how these interactions occur inhibits research into the development of bystander awareness systems to support these interactions, which are often built with little/no evidence of the interaction being designed for actually occurring. Therefore, prior to investigating the design of awareness systems to support bystander-VR user interactions, this thesis first investigates how these interactions currently occur. As an initial step toward this, this thesis first examines how bystanders interrupt VR users.

This chapter describes a survey, Survey 1, which investigated bystanders' comfort enacting and willingness to use five strategies when interrupting a known and unknown VR user in four private/public settings. Additionally, it describes an experiment, Experiment 1, which captured initial insights into how bystanders interrupt a VR user in practice. Experiment 1, through a lab experiment, recreated a bystander interruption of a VR user to investigate how bystanders enact this in practice and to explore the rationale behind bystanders' choice of interruption strategy through post hoc interviews. The goal of this work was to establish how bystanders interrupt VR users and what factors influence their comfort and willingness to use one approach over another when interrupting. The first research question of the thesis aims to address this by asking:

Research Question 1: *When bystanders interrupt a VR user...*

- **1.1.** *how do they enact interruptions?*
- **1.2.** *what factors impact comfort and willingness to enact these interruptions?*

3.2 Survey 1: Design

A survey was conducted to investigate bystander comfort when interrupting a VR user and willingness to use five interruption strategies. The survey investigated these, from the perspective of an interrupting bystander, for the interruption of a known/unknown VR user across four interruption settings.

3.2.1 Survey Structure & Questions

The survey first provided respondents with a description of VR technologies and the survey's purpose. This informed respondents that the survey's goal was to investigate their comfort when interrupting a known VR user (e.g. a friend) and an unknown VR user (e.g. a stranger) across a variety of settings, and to determine how they were willing to interrupt a VR user throughout the presented scenarios. The survey was structured such that respondents were presented with a description of an interruption setting and then were told to imagine they were interrupting a known VR user and then an unknown VR user in this context. The survey investigated four interruption settings (outlined in Section 3.2.2). The order of the interruption settings was presented in a randomised order to respondents.

For each interruption setting, respondents were asked how comfortable they would be interrupting the VR user using a 5-point Likert scale (1=very uncomfortable, 5=very comfortable). Respondents were also asked to report their willingness (binary choice: Yes / No) to each of the following suggested interruption strategies: *Touch, Speech, Gestures, Purpose Built Peripherals, A Keyboard* (outlined in full in Section 3.2.3). An open text field *"Other"* was also included to allow respondents to propose their own interruption strategy if it was not included in the suggested list. Respondents first answered these questions assuming the VR user was known to them (e.g. a friend) and then assuming the VR user was unknown to them (e.g. a stranger). A full copy of the survey is included in Appendix A.

After answering all interruption settings, respondents completed standard demographic data questions. Respondents participation in the survey was voluntary.

3.2.2 Interruption Settings

The survey contained four settings in which the interruption of a VR user was said to take place: *Private Spaces*, *Public Spaces*, *Private Transport*, and *Public Transport*. These settings were chosen as prior works have identified each as locations, beyond the context of

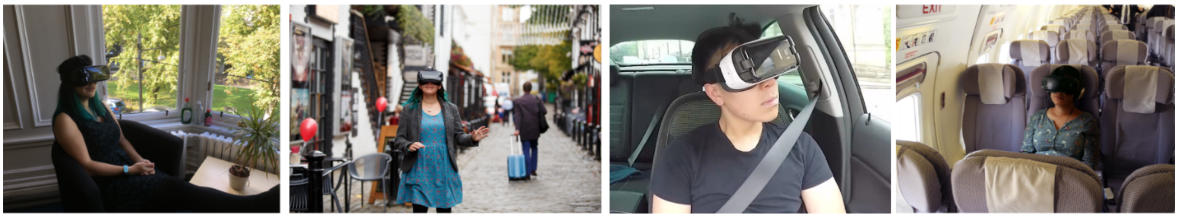


Figure 3.1: The four preview images used within Survey 1. Each image was presented alongside a text description to describe the interruption setting being evaluated to the respondent. From left to right: *Private Space, Public Space, Private Transport, Public Transport*.

a lab study [7], where bystander-VR user interactions will increasingly occur as VR usage becomes more commonplace [76, 40, 11, 41]. For each setting, respondents were provided a textual description of the setting being evaluated accompanied by an image to help the respondents imagine a VR user in this context (Figure 3.1).

3.2.3 Suggested Interruption Strategies

The survey asked respondents if they were willing to use five suggested strategies to interrupt the VR user. The purpose of the interruption was left unspecified. The five strategies were:

- ***Touch:*** e.g. *"Make physical contact with them"*
- ***Speech:*** e.g. *"Speak to them"*
- ***Gestures:*** e.g. *"Wave or gesture at them"*
- ***Purpose Built Peripherals:*** e.g. *"Use a purpose built peripheral for attracting their attention"*
- ***Keyboard:*** e.g. *"Press a key on a nearby keyboard"*

Touch and *Speech* were included as they are the fundamental means by which humans socially interact [113]. *Gestures* were included as an alternative, existing social convention which would allow for interruptions from afar. *Purpose Built Peripherals* were included as Williamson et al received positive feedback towards such devices for enabling easier bystander interruptions of VR users in the context of a passenger flight [76]. Finally, a *Keyboard* was included as a specific example of a peripheral device that respondents would be familiar with.

3.3 Survey 1: Results

3.3.1 Respondents

The survey was distributed using mailing lists and social media and was advertised on a variety of different platforms including VR related subreddits, Facebook groups, VR discord groups, and XR mailing lists. 100 respondents (40 female, 60 male) completed the survey. Respondents ranged in age from 16 to 60 (M=27.45, SD=10.09). Respondents were asked to indicate their prior experience with VR headsets using a 5-point Likert scale (1=none, 5=a lot), (M=2.72, SD=1.36). 76 reported having at least *"a little (2)"* prior experience with VR.

3.3.2 Analysis

Ordinal data was analysed using non-parametric statistical tests, and was followed by pairwise comparisons with Bonferroni corrected p-values [114]. A Friedman test was used to find significant differences between conditions (where appropriate) and pairwise comparisons were performed using Wilcoxon signed-rank tests with Bonferroni corrected p-values. Qualitative data, captured by the *"Other"* field, is presented in full, grouped by thematic relevance, as only nine responses were made to this optional question.

3.3.3 Bystander Comfort When Interrupting VR Users

Table 3.1 summarises the mean (standard deviation) values between the responses to the question investigating respondents' comfort when interrupting a known/unknown VR user across the four interrupting settings. Table 3.1 also summarises the Friedman test results, and where applicable Wilcoxon signed-rank tests, of pairwise comparisons across interrupting setting (e.g. comparing *Unknown VR User (Private Spaces)* and *Unknown VR User (Public Spaces)*, etc).

Comfort Interrupting	*(1) Private Spaces*	*(2) Public Spaces*	*(3) Private Transport*	*(4) Public Transport*	***Friedman Test***	***Wilcoxon Post-hoc (0<0.0083)***
Unknown VR User	2.28 (1.03)	2.06 (1.17)	2.31 (1.10)	2.04 (1.12)	$\chi^2(3) = 24.13$, $p<0.0083$	3-4
Known VR User	4.11 (0.93)	3.93 (1.07)	4.05 (1.00)	3.90 (1.01)	$\chi^2(3) = 5.47$, $p>0.0083$	N/A

Table 3.1: The mean (standard deviation) values, and significant differences, for the comfort interrupting a known/unknown VR user across the four interruption settings.

Known VR User - Unknown VR User Comfort Same Setting Comparisons	***Friedman Test***	***Wilcoxon Post-hoc ($0<0.0083$)***
Private Spaces	$\chi^2(1) = 79.21$, $p<0.0083$	$p<0.0083$
Public Spaces	$\chi^2(1) = 64.00$, $p<0.0083$	$p<0.0083$
Public Transport	$\chi^2(1) = 68.89$, $p<0.0083$	$p<0.0083$
Public Transport	$\chi^2(1) = 67.24$, $p<0.0083$	$p<0.0083$

Table 3.2: Significant difference comparisons between comfort values for interrupting a known VR user and unknown VR user in the same interruption settings. Mean (standard deviation) values for these known/unknown VR user comfort scores in each interruption setting are summarised in Table 3.1.

Respondents reported being comfortable when interrupting a known VR user irrespective of the interruption setting (Table 3.1). Respondents were slightly more comfortable interrupting a known VR user in private settings over public ones but the differences were not significant. Respondents also reported being uncomfortable when interrupting an unknown VR user irrespective of setting. When interrupting an unknown VR user, respondents again were slightly more comfortable interrupting in private settings rather than public. One significant difference was found: between *Unknown VR User (Private Transport)* and *Unknown VR User (Public Transport)*.

Table 3.2 summarises the Friedman test results and Wilcoxon signed-rank tests of pairwise comparisons across relationship to the VR user being interrupted (e.g. comparing *Unknown VR User (Private Spaces)* and *Known VR User (Private Spaces)*, etc). Significant differences were found in all comparisons: between (*Unknown VR User (Private Spaces)* and *Known VR User (Private Spaces)*, (*Unknown VR User (Public Spaces)* and *Known VR User (Public Spaces)*, (*Unknown VR User (Private Transport)* and *Known VR User (Private Transport)*, and (*Unknown VR User (Public Transport)* and *Known VR User (Public Transport)*,

This demonstrates that the primary influence on respondents comfort when interrupting was their relationship to the VR user (e.g. were they known or unknown by the interrupting bystander). As one might expect due to existing social norms [113], respondents were more comfortable interrupting known individuals than unknown. Crucial, however, is the result which indicates that bystanders are comfortable interrupting known VR users (irrespective of interruption setting).

Interruption Strategy	***Private Spaces***	***Public Spaces***	***Private Transport***	***Public Transport***
Counts When Interrupting a Known VR User				
Speech	80	80	80	80
Touch	75	74	77	84
Purpose Built Peripherals	34	31	39	34
Keyboards	26	17	21	19
Gestures	13	19	16	17
Other	2	1	1	0
Counts When Interrupting an Unknown VR User				
Speech	75	68	69	68
Touch	31	34	45	42
Purpose Built Peripherals	35	29	33	36
Keyboard	26	13	14	15
Gestures	12	16	14	17
Other	1	2	0	2

Table 3.3: Counts (out of a possible 100) of respondents willingness to use each of the proposed interruption strategies to interrupt a known/unknown VR user across the four interruption settings. Of note are high rates of willingness to use *Speech* and *Touch* when interrupting a known VR user irrespective of interrupting setting.

3.3.4 Willingness to Use Interruption Strategies

Table 3.3 summarises the counts of respondents willingness to use each of the proposed interruption strategies (outlined in Section 3.2.3) when interrupting a known/unknown VR user across the four interruption settings (outlined in Section 3.2.2).

The results show a high willingness from respondents to use *Speech* when interrupting both known and unknown VR users across all of the interruption settings. Respondents also reported a high willingness to use *Touch* to interrupt a known VR user irrespective of setting. This willingness greatly reduced when interrupting an unknown VR user, further reinforcing that the bystander's relationship to the VR user, rather than the interruption setting, was the primary influence on respondents interruption approach preference.

Interestingly, approximately a third of respondents still indicated they would be willing to interrupt an unknown VR user using *Touch* irrespective of setting. This amount is similar to the number of respondents who indicated they would be willing to use a *Purpose Built Peripheral* to interrupt a known/unknown VR user irrespective of setting. This, highlights some interest in *Purpose Built Peripherals* but also a reliance on existing social norms (e.g. *Speech* and *Touch*) when interrupting irrespective of relationship between the VR user and bystander, and of the interruption setting. *Gestures* and a *Keyboard* meanwhile performed worse with few respondents indicating they were interested in using either to interrupt a known/unknown VR user.

There was nine *"Other"* responses submitted in total. Five suggested alternative approaches to interrupting: two technical systems to interrupt the VR user with, two stating the respondent would attempt to remove the VR user's headset, and one that the respondent would stomp on the ground to create vibrations to gain the VR user's attention:

- *P12: "Message them on a system that leaves a little notification in their FOV" for (Known VR User, Private Space)*
- *P19: "Perhaps some sort of sensor that sends a signal to the VR environment when someone enters a certain radius?" for (Known VR User, Public Space)*
- *P43: "Remove the headset myself. Assuming they were still" for (Known VR User, Private Space)*
- *P62: "Remove the headset myself. Assuming they were still" for (Known VR User, Private Transport)*
- *P89:"Stomping the ground to create vibrations/sound" for (Unknown VR User, Private Space)*

The four remaining comments were respondents stating they would either linger (and not interrupt the VR user) or that they would explicitly not interrupt the VR user in the particular context being considered:

- *P11: "I would linger until they took the headset off" for (Unknown VR User, Public Space)*
- *P24: "I would linger" for (Unknown VR User, Public Transport)*
- *P38: "I don't think I would try to get their attention" for (Unknown VR User, Public Transport)*
- *P75: "I wouldn't get their attention" for (Unknown VR User, Public Transport)*

3.4 Survey 1: Discussion

3.4.1 Bystanders are Comfortable Interrupting Known VR Users Irrespective of Setting

Survey 1's results indicate bystanders are comfortable interrupting a known VR user irrespective of the interruption setting. Furthermore, its results show that a bystander's relationship to the VR user (e.g. whether they are known or unknown by the bystander) is the most influential factor on the bystander's comfort when interrupting. The setting of the interruption, in contrast, was found to have minimal influence on bystander's comfort levels.

Significant also was that bystanders appear comfortable interrupting known VR users using existing, natural interruption methods (e.g. interrupting using *Speech* or *Touch*). While prior works (e.g. [83, 75, 84]) have proposed creating a "transparent HMD" to encourage bystanders to initiate an interaction with a VR user to create a more natural interaction, the results of Survey 1 highlight that such systems may, to a degree, be superfluous as the majority of bystanders are comfortable initiating an interaction with a known VR user verbally or even with physical contact.

3.4.2 Bystanders Preferred Interruption Strategies

Survey 1's results provide initial insights into how bystanders are willing to interrupt VR users. *Speech* (e.g. verbal interruptions) was an approach respondents were willing to use irrespective of the relationship to the VR user or setting. Furthermore, when interrupting a known VR user, *Touch* (e.g. physical contact) scored comparable to *Speech* across all of interruption settings. This, again, reinforces the bystander's relationship to the VR user was the primary influence on their comfort/choice of interruption strategy in Survey 1. Although, it should be noted that this willingness to use *Touch* did reduce significantly when interrupting an unknown VR user across all of the settings, which was expected due to existing social norms surrounding discomfort touching unknown individuals [113].

Despite this increase in discomfort when interrupting an unknown VR user, no increase was seen in respondents willingness to use the suggested alternative interruption strategies (e.g. *Gestures, Purpose Built Peripherals, Keyboard*). Instead, respondents willingness to use these scored comparable irrespective of relationship to the VR user and interruption setting. Of these, *Purpose Built Peripherals* performed best with approximately a third of participants stating they would use such a device. This result is in-line with the findings of Williamson et al who found good results using this approach to facilitate a bystander-VR user interruption in a public transport setting [76]. However, most respondents who indicated they would use *Purpose Built Peripherals* to interrupt also stated they were willing to use *Speech* and/or *Touch*. This, in turn, further reinforces that bystanders are both comfortable with, and and willing to use, existing, established social conventions when interrupting a VR user (e.g. verbal interruptions or physical contact).

3.4.3 The Need to Investigate Bystander Interruption of VR Users in Practice

While Survey 1's results provide initial insights into bystander comfort while interrupting VR users, and how they are willing to interrupt, they are limited. For example, it remains unknown if these interruption attitudes and preferences occur in practice, and the extent to which interruption approaches are used together (e.g. verbally interrupting from afar then following up with physical contact). Furthermore, the rationale behind a bystander's choice of interruption approach remains unknown. Therefore, to explore these open questions, a follow up lab experiment, Experiment 1, was designed to investigate bystander interruption of a known VR user in practice.

3.5 Experiment 1: Design

Survey 1 indicated that bystanders are comfortable when interrupting a known VR user irrespective of the interruption location and are willing to interrupt verbally or with physical contact. However, Survey 1 lacked insight into if these results would actually be seen in practice and the rationale behind how bystander's choose to interrupt the VR user. Therefore, to investigate this a lab experiment, Experiment 1, was designed to replicate a bystander interruption of a VR user.

3.5.1 Design Overview

A lab experiment was designed to replicate the experience of bystander interrupting a known VR user in a private setting. Participants were recruited in pairs (to ensure they knew each other prior to participating in the experiment) and the experiment replicated the scenario of a bystander entering a room and getting the attention of a VR user who was using VR for entertainment purposes. The roles inhabited by participants during the study are outlined in Section 3.5.2.

To investigate what influence a VR user's activity in VR might have on the bystander's interruption approach (e.g. an active, moving VR user vs a passive, stationary VR user) a between-subjects design was used with application type as the independent variable. This experimental design was chosen as it was hypothesized that a more active bystander would deter an interrupting bystander from using physical contact to interrupt (e.g. a VR user constantly swinging their arms would deter the bystander from using physical contact). Two commercial applications were chosen as the two conditions used in the study. These were: a standing, active application (*Beat Saber* [115]), and a seated, passive application (*Epic Roller Coasters* [116]). These are outlined in full in Section 3.5.3.

3.5.2 Participant Roles

As Survey 1 highlighted that the relationship between an interrupting bystander and VR user can influence both comfort when interrupting and choice of interruption approach used, the decision was made to focus the experiment on the interruption of known individuals in a private setting. As such, participants were recruited in pairs to ensure they knew each other prior to participating in the experiment.

During the experiment participants occupied one of two roles:

- ***The VR User:*** A VR user, using VR for entertainment purposes, who is interrupted by the bystander
- ***The Interrupting Bystander:*** A bystander who enters the room and interrupts the VR user

Participants acted out both roles during the experiment (as described in Section 3.5.6).

3.5.3 Application Conditions

The experiment was designed to recreate the affordances and visual/aural demand of home VR entertainment. To achieve this two commercial VR applications were chosen as the *active* and *passive* conditions examined. Two on-rails [117, 118] applications (e.g. short, scripted experiences) were chosen for this to control the VR user's experienced content, position and inputs/actions across participants. One playthrough of each application lasted approximately 3.5 minutes. The conditions are summarised as follows:

- ***Active application:*** *Beat Saber* [115] is a music rhythm game where the user uses slash-like motions to hit targets and avoids in-game hazards by crouching or stepping to the left or right. It requires constant movement/motion from the user as they follow a scripted sequence of actions whilst playing through a song.
- ***Passive application:*** *Epic Roller Coasters* [116] is an on-the-rails VR experience where the user rides a roller coaster. It requires no input from the user beyond starting the application.

3.5.4 Interview Questions

At the end of the experiment a semi-structured interview was conducted (both participants interviewed together) to investigate the rationale behind participants' choice of interruption approach. Participants were asked: (1) to discuss why they had chosen their interruption approach, (2) if they would want some alternative means of interrupting such as a purpose built device or for the headset to detect if they waved at the VR user, (3) if past experience as a VR user being interrupted (during the experiment or otherwise) influenced their choice of interruption approach, and (4) if/how they would act differently if the VR user had been more active or passive in their movement, motion, actions, etc.

3.5.5 Apparatus

An Oculus Quest headset [119] was used to conduct the experiment. The freely available demos of *Beat Saber* [115] and *Epic Roller Coasters* [116] from the Oculus Quest store were used in their respective conditions. During the experiment, participants used the headset's on-board, acoustically transparent [120], audio system. This audio source was chosen, opposed to headphones, to not deter bystanders from attempting a verbal interruption due to the visual image of a VR user wearing headphones (as this may have created the affordance that a verbal interruption would not be heard). The headset volume was set to 53.3% (8 bars out of 15) during the experiment which was a volume that would allow a VR user to hear a bystander's attempted verbal interruption but also one that would create some audio leakage from the VR headset into the user's surrounding environment. This approach was chosen to investigate if the audio leakage from the headset would deter a bystander from attempting to interrupt verbally.

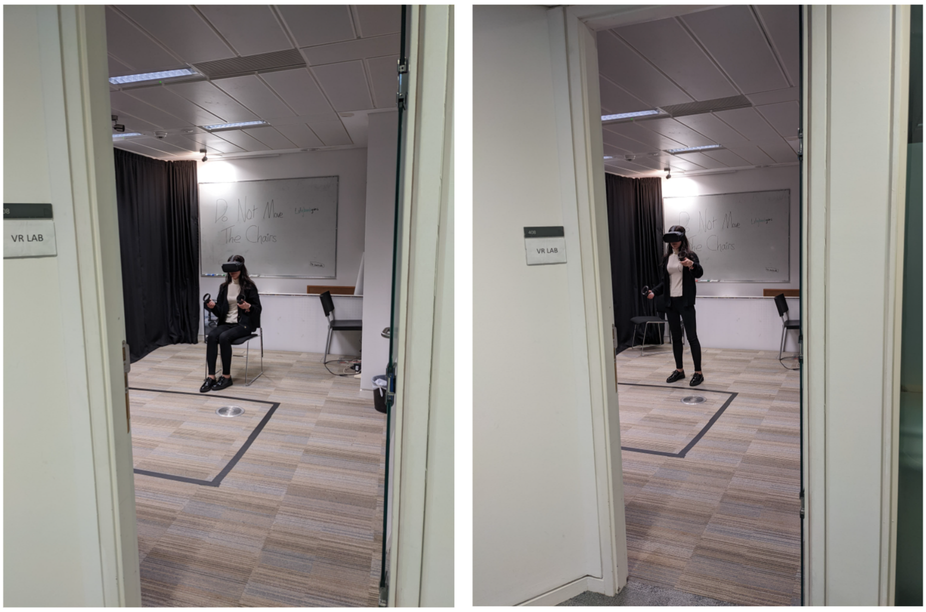


Figure 3.2: Experiment 1's experimental setup. The interrupting bystander's view of the VR user from the room's entrance. Left shows the *Epic Roller Coaster* passive application condition. Right shows the *Beat Saber* active application condition.

3.5.6 Procedure

Upon arrival the experiment's purpose and setup was explained to the participants. Participants were told we were investigating how individuals interrupt VR users and that participants would be doing this as their task. Both of the roles participants would inhibit was then explained to them, and participants when interrupting were told they were free to act as they wished - that we were simply interested in their actions, whatever they may be. The participants were then randomly assigned the role of either the VR user or the interrupting bystander. The participant assigned the role of the interrupting bystander was then removed from the room and given a demographics questionnaire to complete. The application being used, and its controls, was then explained to the participant assigned the role of the VR user. The VR user was then shown (if required) how to put on and fit the headset and was instructed where to sit/stand during the experiment. The experimenter then told the VR user to start the application, started a timer, and exited the room.

After sixty seconds, the experimenter instructed the participant acting as the bystander to enter the room and interrupt the VR user. Sixty seconds was chosen as it corresponded to a moment of high VR user activity in the active application condition (e.g. a sequence of intense slashing motions/movement in-game). The interrupting bystander's view of the VR user from the door of the room as they entered is shown in Figure 3.2. The experimenter observed the interruption approach used during the interruption and recorded notes on it and the VR user's reaction to being interrupted.

Once the VR user's task ended, participants switched roles and the process was repeated. After participants had experienced both roles a semi-structured interview was conducted. Participants were interviewed together and asked to discuss their choice of interruption approach, if they wanted alternative means of interrupting the VR user, and if they would act differently if the VR user's actions were more active or passive. The experiment took approximately thirty minutes to complete.

3.6 Experiment 1: Results

3.6.1 Participants

Participants were recruited using social media and university mailing lists. Participants were recruited in pairs to ensure they knew each other beforehand. 16 participants (11 male, 5 female) in 8 pairs completed the experiment. Participants ranged in age from 20 to 37 (M=24.06, SD=5.05). Participants were asked to indicate their prior experience with VR headsets using a 5-point Likert scale (1=none, 5=a lot), (M=2.75, SD=1.61). 10 reported they had at least *"a little (2)"* prior experience with VR.

3.6.2 Analysis

The qualitative results are based on interview transcripts and observations made by the experimenter during the experiment. Interview transcripts were coded using selective coding [121] where participants' statements were assigned emergent codes over repeated cycles with the codes grouped using a thematic approach. Analysis of the observations recorded by the experimenter followed the same approach. A single coder performed the coding and reviewed/discussed the coding with one other researcher. Three coding cycles were completed.

3.6.3 Observed Interruption Strategies

The observations made by the experimenter during the experiment of how the bystander interrupted the VR user are summarised in Table 3.4. The combined use of *Speech & Touch* (irrespective of order) was the most frequent interruption strategy used by the participants. The application type (e.g. *Beat Saber* vs *Epic Roller Coasters*) did not appear to influence participants interruption strategy in this study (a sentiment reinforced by participants interview comments).

Observation	*Count*
— Active Application Condition (Beat Saber)	
Touch & Speech (irrespective of order)	3 of 8
Speech Only	3 of 8
Playful Interruption	2 of 8
— Passive Application Condition (Epic Roller Coasters)	
Touch & Speech (irrespective of order)	3 of 8
Speech Only	2 of 8
Touch Only	2 of 8
Playful Interruption	1 of 8
— Combined Condition Counts	
Touch & Speech (irrespective of order)	6 of 16
Speech Only	5 of 16
Playful Interruption	3 of 16
Touch Only	2 of 16

Table 3.4: The observations made during Experiment 1 observations of how the bystander interrupted the VR user.

Observation: Unconventional, Improvised, Interruption Strategies

The most significant observation made was that 3 participants, rather than relying on conventional methods of interrupting (e.g. speech or touch), chose to improvise and create a novel, unconventional interruption strategy - termed *"playful interruptions"*. Participants said their intent behind these unconventional interruption approaches was not malicious, rather, they simply wanted to act *"playfully"* with the VR user. The playful interruption strategies observed were:

- 1 participant stealthily approached the VR user then hugged them while shouting their name
- 1 participant approached the VR user then touched them in the back of their knee while whispering in their ear using a fake voice
- 1 participant used a wooden stick they found in the nearby area to prod the VR user

Note: Although these interruption approaches all made use of speech and touch, they are excluded from the counts of *Speech* and *Touch* in Table 3.4 as their intention and usage differed significantly from the conventional use of *Speech* and *Touch*.

Observation: How Participants Approached and Touched the VR User

When interrupting, 12 participants approached the VR user to either touch or speak from a close proximity. 9 participants were confident when approaching the VR user and did so at a regular walking pace. These participants stated they did this as they believed they could, *P7: "safely approach the VR user as they were mostly just in the same place"*.

3 participants approached the VR user cautiously/slowly and stated they were *P3: "concerned the VR user might suddenly move and hit me"*. 1 participant, who began cautiously approaching the VR user to touch, abandoned this interruption approach mid-way through and backed off and switched to a verbal interruption from distance. When asked why they switched their approach the participant said *P1: "I saw them [the VR user] swing their arm pretty close to where I was going so I backed off due to fear of being punched"*.

Participants who used touch when interrupting, excluding the playful interruptions, used either a light touch (3 participants) or tap (5 participants) of the VR user's shoulder while standing at their side. Participants who used a light touch lay their hand on the VR user's shoulder and did not remove it until the VR user interacted with them.

3.6.4 Participant Interviews

Speech/Touch Are Considered Natural Interruption Strategies

5 participants commented that using speech and/or touch when interrupting the VR user was comfortable and felt like the most natural method of interrupting the VR user, *P4: "I mean that's how you get someone's attention"*. 2 participants reported feeling uncomfortable interrupting via touch and so opted to use speech alone. The remaining 9 participants were indifferent towards the use of speech and/or touch, *P11: "you just pick one and use it depending on what they're [the VR user is] doing, either is fine"*.

When asked about alternative methods of interrupting (e.g. using a peripheral device to trigger a notification) most participants were indifferent towards alternative approaches believing they were superfluous. Instead, most participants believed that speech and/or touch was sufficient to interrupt a VR user in most contexts as it was the *P11: "most straightforward, direct"* method of doing so. Although, 1 participant, who had prior experience using a HTC Vive headset [91], when discussing the potential for a peripheral device to trigger a remote interruption referenced the *"Knock, Knock"* feature of the HTC Vive headset [91, 122] stating *P10: "it would be nice if you could trigger that remotely with your phone or something alongside a text message to give them more information"*.

Justifying the Combined Use of Speech and Touch

All participants who used both speech and touch to interrupt said they used both to try and *P12: "reassure"* the VR user being interrupted who they were concerned would feel scared and/or surprised by the interruption. These participants felt by first verbally announcing their presence (to inform the VR user of their existence) and then following up by touching the VR user (to inform the VR user where they were located in the surrounding area) that this would be the most comfortable interruption strategy for the VR user, *P12: "I'd already got his [the VR user's] attention [via speech] but I just wanted to make sure that he knew where I was"*.

Relationship to the VR User was an Influence on Interruption Approach

11 participants said they would be less comfortable interrupting a VR user they did not know and would alter their interruption approach accordingly (e.g. avoiding physical contact, switching to verbal interruptions from afar), *P6: "I'd probably put more emphasis on trying the audible first and avoid touching them as much as possible"*. 1 participant (who worked in a hospital) speculated that they might even change their interruption approach depending on which of their colleagues they were interrupting, *P10: "if it's one of the surgeons I'd be like 'excuse me' but if it was one of my other nurses I'd be tempted to tap them"*.

Room-scale VR Might Influence Interruption Approach

7 participants did not consider the active application (*Beat Saber*) to be *P2: "active enough"* to influence their interruption approach. Participants said this was because the VR user's position was mostly fixed and their movements/gestures limited to arm swings/swipes. As such, participants believed prior to interrupting they could observe and learn the movement/motion patterns of the VR user then identify a safe path to approach, *P4: "I was able to figure out their range of movement and then just made sure to avoid it when approaching"*.

However, room-scale VR applications [34] (e.g. where the VR user walks around a set physical space) were believed to justify a change in interruption strategy from participants. 5 participants elaborated on this, stating they would likely change their interruption approach to be less reliant on touch and more on verbal interruptions from distance, *P6: "if it was like a walk around sim where someone is walking around the space I'd feel less comfortable going up to them and tapping their shoulder"*. Participants explained this was because room-scale applications were less predictable than the applications used in Experiment 1, where the VR user's movement/motions could be learned quickly via observation.

Prior Experience Can Influence the Interruption Approach Taken

6 participants said prior experience (or a lack of) with VR headsets influenced how they interrupted the VR user. Prior experience with the VR headset's built-in, acoustically transparent, on-board audio system highlighted this firsthand in the experiment.

3 participants, who were unfamiliar with the on-board audio system used in the Oculus Quest headset [120, 119] said they were uncertain if the VR user would hear them if they attempted to speak from distance due to the audio being emit from the headset into the surrounding area, *P4: "I thought the VR user wouldn't hear me, I came close because I could hear music [being emit from the VR headset]"*. These participants believed because they could clearly hear the audio being emit from the VR headset that the VR user would be unable to hear them unless they spoke from close proximity. Here, the audio leakage from the headset created a false affordance - that the VR user would be unable to hear a verbal interruption spoken from distance - and is the opposite of its intended purpose (to create a headphone-free experience providing the VR user with an increased aural awareness of their surrounding environment).

However, 3 participants stated because they acted in the role of the VR user first that they realised they would be able to hear someone speaking to them from distance over the headset's audio. This, in turn, motivated their own use of a verbal interruption from distance as they were confident having experienced the on-board audio firsthand that the VR user would be able to hear them, *P14: "being the first one to use it I knew I could just talk and they would probably be able to hear me"*.

2 participants also discussed how prior experiences as a VR user, outside of the experiment, had influenced how they choose to interrupt during the experiment. 1 participant, who opted to use a *playful interruption*, said a past experience being interrupted playfully had inspired their own use of one during the experiment, *P5: "I was going towards what two of my friends were doing when I first tried VR, they were surprise hugging and tickling me, things like that"*. Meanwhile, the other participant, who did not use a *playful interruption*, stated they had considered using one due past experiences being interrupted by a family member in such a manner, *P16: "I could have tapped their [the VR user's] head, that works on me when my sisters do it"*.

Personality Traits Might Influence Interruption Approach

5 participant comments suggested the personality of the interrupter may also influence their choice of, and willingness to perform, one interruption approach over another. For example, 2 participants justified their use of an unconventional, *playful interruption* as their desire to

act playfully/mischievously, *P2: "I wanted to play with them a bit. I was curious to see if I'd get punched or not."*. However, 1 participant, who was the recipient of a *playful interruption*, discussed why they would never use such an unconventional approach, *P6: "I don't have the confidence to inflict that kind of stress on someone"*. This suggests how personality traits may both encourage and deter an individual from using any particular interruption strategy.

Furthermore, 2 participants expressed an unwillingness to interrupt a VR user if their reason for interruption was non-urgent. These participants stated that they assumed that someone using a VR headset must be using it for some specific purpose and so would not want to be disrupted if possible. As such, these participants said if their reason for interrupting was non-urgent that they would likely linger for a short while to see if the VR user took off the headset naturally or leave and return later when the person might no longer by using VR, *P14: "if it wasn't urgent, I'd probably just go away and let them do their thing, I'll come back later, you [the VR user] are busy obviously"*.

3.7 Experiment 1: Discussion

3.7.1 Speech and Touch Were the Preferred Interruption Strategies

The results of Experiment 1 confirm bystanders are a comfortable using speech and touch when interrupting a known VR user. Participants reported speech and touch felt like natural methods of interrupting a known VR user (which is no different than interruptions between two non-VR users [113]). Similar to Survey 1's results, most participants showed little interest in alternative interruption methods which would enable interruptions from afar (e.g. purpose built peripheral devices, recognition of gestures, etc). Instead, as in Survey 1, most believed speech and/or touch would be sufficient for interrupting in most/all contexts.

Noteworthy is that the combined use of both speech and touch was the most frequent method of interrupting used by participants during the experiment. When justifying their use of both, participants said they were concerned with scaring or surprising the VR user. To minimise this, participants felt the best approach would be to first verbally announce their co-presence to the VR user then follow up with physical contact to relay their position. This, in turn, highlights that bystanders are conscious of the VR user's comfort and safety when interrupting, and will often try to minimise any discomfort as much as possible.

3.7.2 Factors Influencing How Bystanders Interrupt a VR User

Participants stated their relationship to the VR user would influence their choice of interruption approach (e.g. being less reliant on physical contact when interrupting an unknown VR user and more on verbal interruptions from distance), This result reinforces the same result in Survey 1 (Section 3.3). Participants also indicated that a VR user using a room-scale application (e.g. one where the VR user moves around a space opposed to being mostly stationary) would likely influence their interruption approach. Again, participants said this would reduce their reliance on physical contact and increase their reliance on verbal interruptions from distance. This finding is in-line with the results of prior work which have indicated a VR user's task can influence their response to a bystander awareness system [56]. Meanwhile, five participants discussed how their personality [123] might influence how they chose to interrupt, with two participants justifying their use of a *playful interruption* as in-part attributable to their personality and one participant stating they lacked the confidence to use a *playful interruption* approach.

Finally, it should be noted that two participants said if their reason for interrupting was non-urgent that they would not interrupt a VR user (who they assumed would not wish to be disturbed) and would return later when they (hopefully) were no longer using VR. George et al. have reported a similar result when they conducted an experiment to investigate if bystanders could determine when a VR user was switching tasks which they posited was the optimal moment for a bystander-VR user interruption to occur. In their work, they reported multiple instances of participants disobeying the experiment's instructions to interrupt a VR user mid-task and instead waited until the VR user naturally removed the headset before interrupting [10]. When George et al. asked their participants why they did not interrupt the VR user mid-task their participants stated they were uncertain if the VR user would want to be interrupted while *"deeply engaged with another device"*. This justification is similar in sentiment to the comments made by participants in Experiment 1 while discussing their reluctance to interrupt VR users for non-urgent reasons.

To alleviate such bystander concerns regarding whether it is appropriate or not to interrupt a VR user, Gottsacker et al. proposed attaching LEDs onto a VR headset as *"activity cues"* to act as status indicators to signal to a bystander whether a VR user wishes to be disturbed or not [82]. Mai et al, meanwhile, proposed *TransparentHMD* to create the illusion of a VR user having a face to encourage bystanders in initiate an interaction with them [75, 83]. Yet, while the solutions proposed by Gottsacker et al. [82] and Mai et al. [75, 83] can effectively encourage a bystander to interact with a VR user, the onus of initiating the interaction remains entirely on the bystander. Additionally, the VR user remains uninformed, and the potential victim to the malicious actions [11], of any bystander in their surrounding environment. Therefore, while such systems to encourage bystanders to interact can reduce a bystander's uncertainty over whether to interrupt or not, there remains open challenges within bystander-VR user interactions which are only resolved by increasing the VR user's awareness of their surrounding environment through bystander awareness systems [6, 9].

3.7.3 Playful Interruption Strategies and Power Imbalances

The most surprising result from Experiment 1 was the emergence of unconventional, improvised interruption strategies, termed *playful interruptions*, used by some participants. During the experiment participants who utilised such a *playful interruption* stated that their intentions was not malicious rather they simply wanted to act playfully with the VR user. However, it should be noted, that such interactions, fundamentally, are reliant on a bystander exploiting an unaware VR user who is in a compromised state where their of their surrounding environment is impaired [6, 9]. Consequentially, one can easily envision scenarios where a malicious bystander exploits the vulnerable state of the VR user by stealing an object in the surrounding environment [11], filming the VR user to post a video of them online and embarrass them [7], or even to intentionally physically harm the VR user (e.g. push them over). Such interactions therefore highlight the power imbalance that exists between an aware bystander and unaware, vulnerable, VR user (who the bystander is often in a position to exploit). And while this imbalance was exploited in Experiment 1 by participants with positive, good-natured intentions, one can easily envision how it might be exploited by malicious bystanders for their own self-interest.

3.8 Conclusions

The research in this chapter presents initial steps towards investigating bystander interruption of VR users: how these interruptions occur, and what factors impact a bystander's willingness and comfort when interrupting.

Survey 1, was presented which investigated bystander comfort, and willingness to use various interruption strategies, when interrupting a known/unknown VR user across four interruption settings. It found a bystander's relationship to the VR user was the most influential factor on the bystander's comfort interrupting and willingness to use an interruption strategy. The interruption setting, meanwhile, was found to have minimal impact. Additionally, Survey 1's results indicate bystanders are comfortable interrupting a known VR user using a verbal interruption or physical contact irrespective of interruption setting. They also indicate bystanders are uncomfortable interrupting an unknown VR user, irrespective of setting, and rely primarily on interrupting unknown VR users verbally.

The results of Survey 1 are limited, however, as they did not investigate whether such insights actually reflect interruptions in practice. Therefore a lab experiment, Experiment 1, was designed to recreate bystander interruption of a known VR user in a private setting in the lab. The results of Experiment 1 reaffirm the results of Survey 1, and report the combined use of a verbal interruption followed immediately with physical contact was the preferred bystander interruption approach. Furthermore, the results provide insights into bystanders' justification behind their choice of interruption strategy, the influence of factors such as the application being used by the VR user, and report the use of unconventional, novel interruption approaches termed *playful interruptions*. These *playful interruptions* were of particular interest as they highlight the potential for a bystander to exploit the compromised, vulnerable state of an unaware VR user, further justifying the need for VR headsets to be equipped with bystander awareness systems as a safety feature to mitigate against such scenarios.

Absent, however, still from our understanding of bystander-VR user interactions (including interruptions) is empirical evidence of these occurring in-the-wild. For example, while bystanders were able to interrupt using both speech and touch in a lab environment, domestic settings are more messy, dynamic, and constrained for space [7, 40, 94]. This, in turn, may influence how interruptions occur (e.g. a bystander may opt to rely more on verbal interruptions from afar as the physical space does not allow a safe approach to touch). It is therefore necessary, before addressing **Research Question 1**, that empirical evidence of bystander-VR user interruptions is considered to ensure a more complete understanding is obtained of how interruptions occur. With this in mind, the following chapter presents Survey 2 which utilises a story survey approach to collect unbiased and unfiltered user accounts of bystander-VR user interactions (including interruptions) from both the VR user and bystander perspective.

Chapter 4

In-The-Wild Interactions Between Bystanders & VR Users

4.1 Introduction

The previous chapter through Survey 1 and Experiment 1 provided initial insights into how bystanders interrupt VR users, their comfort when interrupting, and the rationale behind their choice of interruption approach. Yet, at present, there is little empirical evidence of how interactions (including interruptions) between bystanders and VR users occur in-the-wild. VR users and bystanders must sometimes interact due to uncontrolled, shared, social settings in which VR is used [7, 6, 9]. However, our understanding of these interactions - their purpose, how they are accomplished, attitudes towards them, and where they break down - is limited. This, in turn, inhibits research into developing bystander awareness systems to facilitate bystander-VR user interactions, as little is known about the existing real-world interactions these systems are being designed for and VR use within the real world settings where they might be used. Instead, bystander awareness systems are often designed and tested entirely within the lab with little or no empirical evidence of the bystander-VR user interaction being designed for actually occurring in-the-wild. Hence, an understanding of what and how interactions occur between VR users and bystanders in-the-wild is absent. Addressing this gap with empirical data is essential then as it will provide a better, more complete, understanding of bystander-VR user interactions, and enable the design of better, more informed, bystander awareness systems to facilitate these interactions.

This chapter presents a survey, Survey 2, which investigated the context of how bystander-VR user interactions occur in-the-wild. The survey used a user story approach to collect anonymous, unbiased and unfiltered, actual stories of emergent VR user and bystander interactions from both perspectives: the VR user (the individual using the VR device) and the bystander (some non-VR person interacting with the VR user). Its goal was to establish and obtain empirical evidence of the types of interactions which occur between bystanders and VR users in-the-wild and to identify common impediments encountered during these interactions. The study presented in this chapter, in tandem with work presented in the previous chapter (Survey 1 and Experiment 1), is used to address the first research question of this thesis which asks:

Research Question 1: *When bystanders interrupt a VR user...*

- **1.1.** *how do they enact interruptions?*
- **1.2.** *what factors impact comfort and willingness to enact these interruptions?*

However, Survey 2's focus was not limited exclusively to bystanders interrupting VR users, rather, it sought to investigate a wider range of bystander-VR user interaction types and impediments on these interactions. Therefore, the work of this chapter also addresses the second research question of this thesis which asks:

Research Question 2: *When bystanders and VR users interact...*

- **2.1.** *what is the context of the interaction?*
- **2.2.** *what impediments are encountered when interacting?*

4.2 Survey 2: Design

A survey was designed to capture unbiased and unfiltered user accounts of bystander-VR user interactions. The survey collected anonymous, actual stories of emergent VR user and bystander interactions from both perspectives: the VR user (the individual using the VR device) and the bystander (some non-VR person interacting with the VR user). The survey also collected respondents' attitudes towards bystander-VR user interactions to investigate, from the perspective of an bystander interacting with a VR user, comfort while interacting and what information (if any) they would want to know about the VR user.

4.2.1 Methodology

A survey was devised to collect stories of actual VR user and bystander interactions based on the *critical incident technique* [124]. This technique allows for *"generating a comprehensive* *and detailed description of a content domain"* [125] where respondents are asked to recall and tell a story of an experience they have had related to an incident of interest being studied. This approach was chosen as prior work has shown asking sensitive questions in self-report should be done in an indirect and anonymity-preserving way to minimise social desirability bias [126, 127]. For example, the survey refrained from using words such as *"abuse"* or *"spy"* when referring to a bystander's possible actions towards the VR user. This approach was also used to avoid targeting any particular context and to minimise recall bias within the collected responses as much as possible. For example, if the survey had specifically highlighted VR use in home settings, respondents may have been biased to recalling situations that happened in households. To address this, the survey refrained from specifying individual contexts.

The critical incident was presented as a sketch of an intentionally generic VR user and bystander interaction with two stick-figures labelled *"VR user"* and *"non-VR bystander"*, shown in Figure 4.2, alongside a short description which gave clear, labelled, anonymous roles for participants to use in the stories if desired. The survey did not specify any particular *"type of interaction"* between the VR user and bystander to avoid giving respondents the impression there was a *"correct"* type of interaction they were being asked to describe thus potentially discourage them from describing others. The survey was designed using an iterative process to ensure any questions that induce recall or social desirability bias were reworded, and was tested using a pilot test with a small participant samples (N=15).

4.2.2 Limitations of Self-Report

Self-report is a common and established research approach in a diverse range of research areas [128, 129], however, it is not without its limitations. Self-reported data is susceptible to inaccurate statements, influenced by wording or recall bias [130]. Additionally, when asking individuals to self-report potentially sensitive experiences, social desirability can introduce error [131]. Finally, a single study cannot claim to include all possible bystander-VR user interactions.

Although one cannot rule out any of these limitations entirely, measures were taken to minimise their potential impact. The questioning approach used in the survey allowed for anonymity and questions were designed in an iterative process. To identify invalid responses, all collected responses were manually inspected before analysis. Finally, a broad range of feedback was captured for greater ecological validity when contrasted with other published datasets (e.g. the *"VR Fails"* dataset [7]).

4.2.3 Survey Structure & Questions

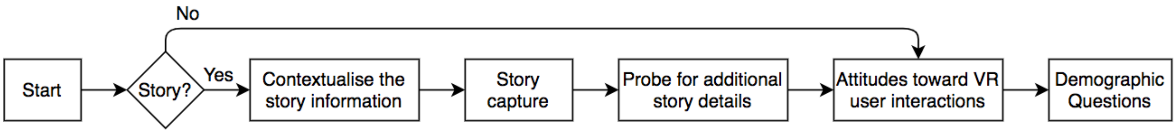


Figure 4.1: A flowchart outlining the structure of Survey 2.

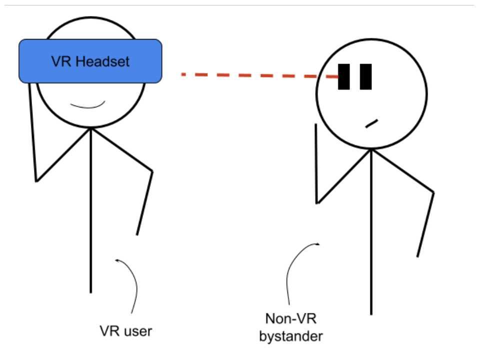


Figure 4.2: The sketch used in Survey 2, presented with the following description: *"With the rise in popularity of VR headsets, interactions between VR users and non-VR bystanders are becoming more frequent. However, little is currently known about how VR users and nearby people interact with one another. The goal of this survey is to capture stories of real experiences you have had as a VR user or bystander when interacting with the other."*

The survey consisted of two parts, a first part to capture respondents story of a bystander-VR user interaction and second to investigate general attitudes towards bystander-VR user interactions. An overview of the survey structure is provided in Figure 4.1. The survey is provided in full in Appendix B.

The survey first determined if respondents had a story to share. A sketch and description (Figure 4.2) was displayed and respondents were asked to state whether they had experienced or observed a real situation similar to this (*Yes: as the VR user, as the non-VR bystander, as both VR user & non-VR bystander, as a third party observer* or *No*). If *"No"*, respondents were automatically routed to the final part of the survey where their attitudes towards interactions with a VR user, as a bystander, was investigated using a series of questions[1].

If *"Yes"*, respondents were then asked a series of 5-point Likert scale questions to contextualise their story: *"how often they experience a situation like this"*, *"how frustrated they typically are during these interactions"*, and *"how often they feel the need to interact with a VR user"*. Respondents were then asked to describe the situation in as much detail as possible via free text entry. Next, respondent were asked to provided specific details about interaction which could be used to indirectly derive further insights about the situation: *"where the interaction took place" (free text entry), "what the VR user / bystander did" (free text entry),*

[1]Note: no respondent selected this option, all shared a story of a bystander-VR user interaction

"how they reacted" (free text entry), "if they knew each other" (Yes, No, Not sure), and *"to state their role within the story" (the VR user, bystander, or a third party observer)*. Multiple choice was used where appropriate but most questions allowed for free text entry.

Respondents were then asked eight questions to investigate their attitudes towards bystander-VR user interactions. Respondents were told to answer these from the perspective of a bystander. First, their *"comfort"* during an interaction was captured, using a 5-point Likert scale (1=Very Uncomfortable, 5=Very Comfortable), for three contexts: *"interrupting a VR user"*, *"avoiding a VR user in a shared space"*, and *"navigating past/around a VR user"*. Next, their *"perceived isolation"* from the VR user was captured using a 5-point Likert scale (1=Not at all, 5=All the time). The same scale was then used to capture the extent to which respondents were *"bothered"* when interacting with a VR user due to: *"the lack of eye contact"* and due to *"the VR user's occluded face"*. After this, an open text field was provided and respondents were asked if they had any comments or feedback relating to their comfort when interacting with a VR user.

Respondents were then presented with a multi-choice question (choose any) asking which of the following they would want to know about a nearby VR user: *"visual content (e.g. what they see)", "aural content (e.g. what they hear)", "awareness of reality (e.g. if they know you are there)", "content type (e.g. what they are doing: playing a game, working, etc)", "interruptability (e.g. do they want to be disrupted)"*, and *"time in VR (e.g. how long they have been in VR for)"*. A free text field *"Other"* was included to allow respondents to enter their own option(s) not included in the list of presented choices.

Finally, respondents completed standard demographic data questions and were asked to indicate their prior experience with VR headsets using a 5-point Likert scale. Respondents could also optionally sign up for a raffle to win one of two £20 Amazon vouchers.

4.3 Survey 2: Results Overview

To aid readability, the results summarising respondents stories and the results to the questions investigating respondents attitudes towards bystander-VR user interactions more generally are separated across two sections. The results of respondents stories are presented in Section 4.4. The results of respondents attitudes towards bystander-VR user interactions are presented in Section 4.5.

4.3.1 Respondents

The survey was distributed through mailing lists and social media and was advertised on a variety of different platforms including VR related subreddits, Facebook groups, VR discord groups, and XR mailing lists. 100 respondents (31 female, 68 male, 1 fluid) completed the survey. Respondents ranged in age from 16 to 68 (M=27.96, SD=8.13). Respondents were asked to indicate their prior experience with VR headsets using a 5-point Likert scale (1=none; 5=a lot), (M=3.91, SD=1.05). All reported they had at least *"a little (2)"* experience with VR.

4.4 Survey 2: Respondents Story Results

4.4.1 Analysis

The data was analysed to investigate the types of interaction reported as occurring between VR users and bystanders within the story responses and to determine the emergent themes within them. Respondent stories were coded using selective coding [121] where respondents' statements were assigned emergent codes over repeated cycles with the codes grouped using a thematic approach. Multiple coding was allowed, meaning statements could be encoded as multiple categories, e.g. [for location data] *P48: "Exhibitions, home, work"* was coded as "Public Spaces" (because of *"Exhibitions"*), "Home" (because of *"home"*), and "Office / Workplace" (because of *"work"*). A single coder performed the coding and reviewed the coding with one other researcher to resolve unclear codes and discuss the depth and specificity of codes. Two coding cycles were completed.

Prior to the conducting the analysis the data was inspected and any invalid responses were removed. For example, responses which were entirely blank or lacked sufficient detail were removed (e.g. an initial story of a few words with then blank responses to all follow up questions). The consistency of respondents responses was also checked (e.g. that responses to follow up questions were consistent with their initial story described). This review process flagged 16 responses which were removed from the data set. This left 100 valid stories to be analysed.

(1) Have you experienced or observed a real situation similar to this?	Count
Yes, I was the VR user:	23
Yes, I was the non-VR bystander:	4
Yes, as both the VR user and non-VR bystander:	73
Yes, I was neither but I observed such a situation:	0
No:	0

(2) How often have you experienced a real situation like this?	Count
Never:	0
A little:	27
Occasionally:	38
Often:	22
All the time:	13

(3) How often have you felt the need to interact with a VR user?	Count
Never:	15
A little:	32
Occasionally:	34
Often:	15
All the time:	4

(4) How frustrated do you feel during VR user and non-VR bystander interactions?	Count
Not at all:	54
Slightly frustrated:	34
Somewhat frustrated:	9
Frustrated:	1
Very frustrated:	2

(5) Did your story involve verbal communication and/or physical contact?	Count
Physical contact and verbal communication:	49
Verbal communication only:	46
Physical contact only:	5
It involved neither:	0

(6) Did the VR user and non-VR bystander know each other?	Count
Yes:	93
No:	6
Not sure:	1

(7) Were you the VR user, the non-VR bystander or someone else?	Count
I was the VR user:	51
I was the non-VR bystander:	49
I was neither (a third party):	0

Table 4.1: The questions asked in Survey 2 to contextualise respondents stories.

4.4.2 Contextualising Respondents Story Data

Respondents Experience With/During Bystander-VR User Interactions

Most respondents (73 of 100) indicated they had experienced or observed a bystander-VR user interaction as both VR user and bystander (Question 1, Table 4.1). When asked how often they had experienced these interactions, using a 5-point Likert scale (1=never, 5=a lot), most reported it *"occasionally"* happened to them (M=3.21, SD=0.99, Question 2, Table 4.1). When asked, as a bystander, how often they felt the need to interact with a VR user (1=never, 5=all the time) most indicated this *"occasionally"* happened (M=2.61, SD=1.04, Question 3, Table 4.1). Finally, when asked how frustrated they felt during bystander-VR user interactions, using a 5-point Likert scale (1=not at all frustrated, 5=very frustrated), surprisingly, most respondents (88 of 100) were at most *"slightly"* frustrated during interactions (M=1.63, SD=0.85, Question 4, Table 4.1). This was unexpected as *"problematic interactions"* are often used to justify building systems in the literature [6, 83, 75] and suggests in-situ evaluations of such systems may be increasingly important.

Communication Methods and the Relationship Between VR User and Bystander

To further contextualise the story data, respondents were asked three questions to provide a general overview of the interaction being described in their provided story. First, respondents were asked if the story described involved physical contact and/or verbal communication (Question 5, Table 4.1). Verbal communication alone or used in combined with physical contact accounted for most (95 of 100) interactions. Next, respondents were asked if the VR user and bystander knew each other, (Question 6, Table 4.1). Respondents reported that most did (93 of 100). Finally, respondents were asked to state their role within the story being reported (Question 7, Table 4.1). An almost even split of respondents being the VR user or bystander was reported (51 reported as being the VR user, 49 as being the bystander).

The Locations Where Interactions Occurred

Respondents were asked to report the location of where the interaction described in their story occurred. From this four high level location types were identified (Table 4.2). In total 111 locations were mentioned by respondents with 94 respondents stating 1 location and 6 stating multiple locations. As expected, most interactions occurred within the home, although 29 instances of locations outside the home were also reported. 20 of these were workplace settings (Office / Workplace and Universities / Research Labs) while 9 were public spaces (composed of *Conference-type events: 4, VR arcades: 3, Museums: 1, Planes: 1*).

Where did the story take place?	Count
Home:	82
Office / Workplace:	11
Universities / Research Labs:	9
Public Spaces:	9

Table 4.2: The coded locations of where described interactions occurred in Survey 2. As expected, most were at home although a variety of locations outside the home were also mentioned. Some respondents provided more than one location.

4.4.3 Categorising How Interactions Occurred

Respondents story data was first analysed by categorising the general types of interactions described by respondents to give a high level overview of the types of interactions captured in the data. Three high level interaction types were identified:

- ***Coexisting:*** the bystander and VR user share the same physical space and one interacts with the other for some reason
- ***Demoing:*** the bystander is demonstrating VR to the VR user
- ***Interrupting:*** the bystander interrupts the VR user

While most stories contained only one high level interaction type, some stories contained multiple, summarised in (1) in Table 4.3, e.g. *P30: "New or casual users needing assistance with controls, game direction, or just chatting. When I'm playing, my girlfriend and I will chat"* was coded as *"Coexisting + Demoing"*.

Coexisting: was the most prevalent interaction type, included within 54 stories with 79 scenarios described. The *Coexisting* interactions described are summarised in (2) in Table 4.3. A range of interactions were identified within this theme, highlighting the diverse range of ways VR is already being used around bystanders: as something to ignore, as something to observe, and/or as something to directly engage with. All, however, described interactions where the bystander and VR user occupy the same physical space for a (prolonged) period.

Demoing: was included in 36 stories highlighting that despite VR becoming more widespread [37, 36] that showcasing the technology to individuals remains a frequent interaction.

Interrupting: was included in 21 stories, with (3) in Table 4.3 breaking down how interruptions occurred. The preference towards verbal interruptions matches results of Chapter

3 (Survey 1 and Experiment 1), although, the combined use of verbal communication and physical contact was not as prevalent as in Experiment 1. Although, it should be noted that respondents who used both verbal and physical contact when interrupting used the same rationale as the participants in Experiment 1 (e.g. to comfort/reassure the VR user being interrupted and to relay the bystander's position in the surrounding environment to the VR user after establishing their co-presence, *P41: "Verbal and physical communication was used to establish presence and location"*).

(1) High level story classification	**Count**
Coexisting:	43
Demoing:	28
Interrupting:	17
Coexisting + Demoing:	8
Coexisting + Interrupting:	3
Demoing + Interrupting:	1
(2) How coexisting occurred	**Count**
Coexisting:	**79**
- Bystander watches / reacts to VR user:	43
- Bystander ignores VR user / converses with them about things unrelated to VR experience:	21
- Bystander and VR user take turns using headset:	10
- Bystander plays multiplayer game with VR user:	5
(3) How interruptions occurred	**Count**
Interrupting:	**21**
- Verbal communication alone:	12
- Physical contact alone:	5
- Verbal communication and physical contact:	4

Table 4.3: The coded classifications of the interaction types from Survey 2. (1) shows the story classification for the high level types of interactions that occurred. Each story maps to 1 code, e.g. *Coexisting* includes stories containing only the *Coexisting* theme whereas *Coexisting + Demoing* contains stories with instances of both themes. (2) breaks down the scenarios which occurred within the *Coexisting* theme. (3) breaks down how bystanders interrupted VR users.

4.4.4 Impediments Encountered During Bystander-VR User Interactions

When Bystanders Interrupt VR Users

8 of 21 the interruption stories explicitly stated the VR user was surprised by the bystander's interruption. 5 of these involved physical contact, 3 involved verbal communication alone. The latter was surprising as a typical verbal interaction (e.g. a bystander entering the room and saying *"hello"*) is not often proposed as a method of surprising or scaring a VR user. However, as these stories highlight, the immersive nature of VR combined with an unexpected interaction with reality (e.g. the bystander entering and speaking) can, even through verbal communication alone, cause the VR user to be surprised and/or scared.

Interestingly, 1 story described the bystander waiting for the optimal moment to interrupt the VR user, *P31: "She [the bystander] knows she have small windows of opportunity to reach me, usually between songs in Beat Saber... Waits for opportunity to reach me based on the amount of waving of my arms"*. This story is similar to the work of George et al. who investigated whether bystanders could identify low activity moments in a VR user's application usage which they posited were the *"ideal moments for interruption"* [10]. While George et al. assumed this behaviour might take place in real world interactions [10], this story confirms that it indeed takes place in real world scenarios.

When Bystanders Demonstrate VR and Guide Users Through an Experience

37 stories reported scenarios where the bystander was demonstrating VR to the VR user. 24 involved the bystander assisting the VR user with the controls of the application and VR headset in use. Issues controlling VR stemmed from the VR user's unfamiliarity with the controller being used and the VR user being unable to see the controller while in VR, *P5: "When using the headset, controls arent visible"*. Issues were also caused due to individuals not understanding how the controls worked conceptually, *P94: "a lot of people new to VR seem to think it's just shake controls like on the original Nintendo Wii"*. To solve these issues, the bystander was required to intervene and show the VR user how to use the controller, *P30: "they usually ask for help with control and i will place their hands in the proper position"*.

21 stories involved a bystander providing verbal instructions to guide a VR user through the application being used, *P1: "I was sat next to them giving them instructions of what to do in the VR game"*. However, frustration was noted as being created here due to the bystander being unable to easily point at objects in the VR user's virtual environment (6 stories), *P33:*

"trying to explain/point out/help them can be frustrating when they can't see what you're indicating or they aren't looking at what you need them to". As a consequence of this, the process often became one of trial and error, *P9: "trying to indicate an action like look up, no there, to the left, not so low, up..."*.

During Verbal Bystander-VR User Interactions

12 stories reported a VR user having difficulty hearing a bystander's attempt to verbally interact with them. 8 of these described situations where the bystander was required to shout as the VR user could not hear them over the VR application's audio, *P27: "The bystander usually tries to help them by yelling at them (often trying to be louder than the game in the VR users ears)"*. The remaining 4 indicated the VR user missed the bystander's verbal interaction entirely, *P17: "They'll call to me, which under normal circumstances would get my attention, but whilst in VR, I often can't hear them"*. Both of these provide real world evidence which reinforces work by Ghosh et al. who identified awareness of nearby audio as one of the key elements of reality VR users desire to be informed of [9], and further motivates the development of bystander awareness systems specifically designed increase a VR user's aural awareness to facilitate verbal interactions between VR users and bystanders.

Physical Transitions to Reality to Facilitate a Bystander-VR User Interaction

19 stories indicated the VR user transitioned (either fully or partially) to reality when interacting with a bystander. This was because the VR user felt that the VR headset was intruding on their ability to interact effectively with the bystander. 6 of the stories described a partial transition to reality: the removal of headphones (2 stories), and temporarily peeking out form under the headset (4 stories), *P42: "Pull the speaker away from one ear to better hear them because it's usually a little too loud"*. The remaining 13 described full transitions to reality: turning on the passthrough view of the headset (2 stories), and complete removal of the headset (11 stories), *P6: "I [the VR user] reacted by removing my headset, and going off to talk to them"*. These stories provide direct empirical evidence that VR users want increased bystander awareness during interactions and, crucially, demonstrate the design of existing VR headsets are insufficient for their needs (e.g. removing the headset to facilitate a verbal interaction due to the insufficient aural awareness provided by the on-board, acoustically transparent, headset design).

4.4.5 The Bystander's Position of Power Over VR Users

Bystander Filming the VR User

2 respondents indicated that they had recorded video of a VR user. Both indicated their intention was not malicious, rather, it was their natural response because of how enjoyable their experience watching VR user's reactions was, *P73: "I saw many phones recording the experience [watching the VR user]... I didn't know it would be so much fun watching just reactions from vr users from my friends and family"*.

As highlighted by Dao et al's work [7], bystanders recording a VR user is not an uncommon phenomenon. Missing, however, is the VR user's perspective - are they comfortable with their actions being recorded without their consent or knowledge and potentially shared online? Furthermore, although Survey 2's respondents indicated their intentions were not malicious, this is not always true [11]. Bystanders could, for example, shoulder surf VR authentication [132, 133] or film the VR user for their own malicious usage, e.g. attempting to shame or embarrass the VR user by posting the video online [7]. This further reinforces the need both to develop usable, secure authentication systems for VR which are resistant to such video recording attacks [11], but also the need increase a VR user's bystander awareness more broadly to prevent the VR user from unknowingly, and non-consensually, being filmed by a (potentially malicious) bystander.

Bystanders Abusing Their Position of Power Over the VR User

Experiment 1 provided initial insights into how a bystander may take advantage of a VR user's vulnerable, unaware, state and improvise a novel, unconventional interactions with them (e.g. improvising a *playful interruption* strategy, Section 3.6). 12 stories captured by Survey 2 reported similar novel, unconventional interactions occurring.

10 stories described scenarios where the bystander touched the VR user to intentionally scare or tease them, *P47: "sometimes the friend outside of VR would want to tease or scare the friend in VR by touching them"*. 9 of these were spur of the moment decisions by the bystander upon seeing the VR user's vulnerable, unaware state. 1, however, was in direct response to the VR user's application in use which the bystander had observed and planned, *P49: "in a scenario on top of a mountain, I moved towards the edge of a cliff to see how realistic it was. Just as I was nearing the precipice, one of my friends pushed me 'off the cliff' to my doom, and then laughed at my misfortune. This was very frustrating"*.

Additionally, 1 story described a bystander who mimicked the VR user's actions because they thought these were amusing, *P19: "The bystander is staring at me at a distance, laughing and mocking my physical movements"*. Finally, 1 story saw the bystander playfully surprise the VR user in an attempt to contribute and enhance their experience in VR. Here the VR user, whose application involved a candy-like land virtual environment, was surprised by the bystander who fed them a cookie to eat, *P83: "I got a cookie. Them walked over to him and told him to open his mouth. Without telling him what it was I put the cookie in his mouth."*.

While this last story is an example of a positive interaction between the bystander and VR user, the aforementioned 11 are more exploitative in nature. While some bystanders stated the intention behind their unconventional interaction was to *"tease"* the VR user (likely in a playful manner similar to participant's sentiments in Experiment 1, Section 3.6), all of the described interactions are reliant on exploiting the VR user who is in a compromised state where their awareness of their surrounding area is impaired. While in this state, the VR user is more vulnerable to the acts of others and a power imbalance is created between the (unaware) VR user and (aware) bystander which can be exploited. In respondents submitted stories, the more malicious interactions described ranged from *"teasing"* to abusive physical contact (e.g. pushing an unaware VR user) but other more exploitative behaviours such as theft of personal possessions [11] or more abusive physical assault could have occurred.

4.4.6 Managing the Physical Space in Which VR is Used

Bystander Intervention to Prevent Accidents and Collisions

In 28 stories, respondents said they felt it was the bystander's responsibility to manage the physical space of the VR user. 19 of these stories reported instances where the bystander directly managed the physical space of the VR user. This involved the bystander watching the VR user, and any other nearby bystanders, and either: redirecting the VR user back into the play area away from objects or people in the nearby area, *P46: "I'll let my friend know if they need to recenter themselves, or if they're too close to a chair or dresser"*, or redirecting nearby bystanders away from the VR user's play area, *P21: "[the VR user] was playing Superhot on the headset, while the others [the bystanders] were watching. However, the others were in the way, so I had to move them while my friend played while also avoiding her myself"*.

The remaining 9 stories discussed the need for bystanders to be mindful of the VR user and that it was the bystander's responsibility to maintain a safe distance from the VR user and negotiate when entering the VR user's play area, *P37: "There are some courtesies I think people should adopt when interacting with a VR user, and that's generally not standing close enough to get accidentally hit, or unwanted or unexpected touching"*. Further exploring these expected courtesies between VR user and bystanders is one opportunity for future work, that is beyond the scope of this thesis, and is a natural progression from the existing work done in the literature (e.g. Geroge et al's work investigating if bystanders can identify an optimal moment to interrupt a VR user) and the works presented in Chapters 3 and 4.

VR User Accidental Collisions With Reality

Despite some bystanders acting as an overseer of the physical space, accidental collisions between the VR user and nearby objects or people do occur [7] and require safety awareness systems to prevent them (e.g. [15, 6, 18]). However, only 5 such unintentional collisions with reality were reported within respondents stories. All featured an accidental collision between a bystander and VR user, *P60: "While my girlfriend was watching me play a VR game, she came too close to my play area, resulting in me accidentally striking her with my controller"*. Additionally, all followed this pattern where the bystander approached or attempted to navigate past the VR user and was then accidentally struck by the VR user. That only 5 stories of this type were reported was somewhat surprising given Dao et al. reported many of their *"VR fail"* videos were accidental collisions between the VR user and reality [7]. Survey 2's results suggest, however, that it is much more frequent for bystanders to intervene and prevent such collisions rather than allow them to occur (albeit off camera)

Physical Indicators Of The VR User's Play Area

Interestingly, 2 respondents described including physical, visible indicators of the VR user's play area within their real world environment. Both respondents said they used a rug/carpet to act as a visible identifier for bystanders of the VR user's play area, *P23: "She [the bystander] knows not to step on the carpet as I may accidentally make physical contact unintentionally"*. This highlights some of the creative solutions individuals develop to accommodate the introduction of VR in their home, and is similar in sentiment to the custom interruption strategies some individuals develop to fit the needs of their particular household (e.g. an individual having phone in their pocket set to vibrate and having their (non-VR) partner call them to interrupt [134]).

4.4.7 VR User Interactions With Bystanders

Pets Can Create Problematic Interactions Too (Non-Human Bystanders)

Although respondents were asked about interactions with (human) bystanders, 2 respondents discussed interactions with pets in addition to (human) bystanders, *P41: "Pets don't really understand VR, and its not uncommon for a cat or dog to come in and sit by my feet while I'm using a VR headset. This can cause some minor issues, like tripping or prodding"*. As the stories highlight, pets may be unaware of the human's lack of visibility of reality, and consequently may put themselves or the VR user in danger. While prior works have explored increasing a VR user's awareness of their surroundings, they focused exclusively on nearby objects and people [72]. Absent, however, is increasing awareness of pets, despite how common they are within the household [135] and future work, that is beyond the scope of this thesis, is necessary to investigate methods of increasing awareness of these non-human bystanders.

Bystander Becomes a Haptic Proxy for the VR User

1 story highlighted how a VR user and bystander can collaborate to intentionally create a novel experience for the VR user, *P84: "I don't remember how [we] thought of it but we ended having sex with him wearing the headset. The Waifu game let you set the Avatar anywhere in the play space and had animations so that it would move. So he laid down and I got top and he set the Avatar in the right place."*. This shows the effort some VR users and bystanders will go to to create novel, consensual experiences for each other, and its use of a bystander as a haptic proxy is similar to Cheng et al's *Haptic Turk* system where four individuals manually carried, tilted and pushed a player's limbs and torso to provide haptic feedback for their gameplay experience [136].

4.5 Survey 2: Attitudes Towards Interactions Results

4.5.1 Analysis

For responses to the Likert-scale questions, mean and standard deviation values were calculated and the distribution of responses examined. For the open text field question, as before, respondents answers were coded using selective coding [121] where respondents' statements were assigned emergent codes over repeated cycles with codes grouped using a thematic approach. Multiple coding was allowed meaning statements could be encoded within multiple groups. A single coder performed the coding and reviewed the coding with one other researcher to resolve unclear codes and discuss the depth and specificity of codes. Two coding cycles were completed.

4.5.2 Bystander Attitudes Towards Interacting With VR Users

Table 4.4 summarises the responses to Survey 2's questions to investigate respondents general attitudes, as a bystander, towards interactions with a VR user.

Comfort as a Bystander Interacting With a VR User

When asked how comfortable respondents were getting a VR user's attention, using a 5-point Likert scale (1=very uncomfortable, 5=very comfortable), 73 respondents said they were at least *"comfortable"* interrupting the VR user (M=3.92, SD=0.93, Question 1, Table 4.4), a similar result as noted in Chapter 3 and Survey 2's story data. When asked how comfortable they would be avoiding a VR user (e.g. doing a task in the same room as them), using the same scale, respondents comfort decreased with only 52 stating they would be, at least, *"comfortable"* in this scenario (M=3.45, SD=1.23, Question 2, Table 4.4). Furthermore, when asked how comfortable they would be navigating past/around a VR user, using the same scale, respondents comfort decreased again, slightly, with 49 stating they would be, at least, *"comfortable"* in this scenario (M=3.33, SD=1.33, Question 3, Table 4.4). While there is an observed drop in comfort with the latter 2 questions it should be noted that approximately half of respondents remain comfortable in both scenarios, a result that is also similar to the findings of Chapter 3 and Survey 2.

Perceived Isolation as a Bystander From a VR User

When asked how isolated, as a bystander, respondents felt around a VR user, using a 5-point Likert scale (1=not at all, 5=extremely), 61 respondents were at most *"slightly"* isolated (M=2.19, SD=1.00, Question 4, Table 4.4). Furthermore, when asked if a lack of eye contact with the VR user was bothersome whilst interacting, using the same scale, 83 respondents were at most *"slightly"* bothered by this (M=1.64, SD=0.85, Question 5, Table 4.4). Additionally, when asked if the occluded view of the VR user's face was bothersome, using the same scale, 88 respondents were at most *"slightly"* bothered by this (M=1.43, SD=0.79, Question 6, Table 4.4).

(1) How comfortable are you getting a VR user's attention?	**Count**
Very Uncomfortable:	0
Uncomfortable:	10
Neither Uncomfortable or Comfortable:	17
Comfortable:	44
Very Comfortable:	29

(2) How comfortable are you avoiding a VR user (e.g. doing a task in the same room as them)?	**Count**
Very Uncomfortable:	5
Uncomfortable:	22
Neither Uncomfortable or Comfortable:	21
Comfortable:	27
Very Comfortable:	25

(3) How comfortable are you navigating past/around a VR user (e.g. moving past or near them)?	**Count**
Very Uncomfortable:	7
Uncomfortable:	29
Neither Uncomfortable or Comfortable:	15
Comfortable:	22
Very Comfortable:	27

(4) To what extent do you feel isolated from a VR user?	**Count**
Not at all:	30
Slightly:	31
Somewhat:	31
Very:	6
Extremely:	2

(5) Does lack of eye contact with a VR user bother you (e.g. when you speak to them / are around them)?	**Count**
Never:	56
Infrequently:	27
Sometimes:	15
Often:	1
All the time:	1

(6) Does the occluded view of a VR user's face bother you (e.g. when you speak to them / are around them)?	**Count**
Never:	72
Infrequently:	16
Sometimes:	10
Often:	1
All the time:	1

Table 4.4: The distribution of responses to Survey 2's attitudes towards interaction questions.

As a bystander, would you want to know this information about a nearby VR user?	Count
Visual Content: *(e.g. to see what the VR user sees in VR)*	73
Awareness of Reality: *(e.g. if the VR user has been notified of your co-presence)*	69
Interruptibility: *(e.g. does the VR user want to be disrupted)*	61
Aural Content: *(e.g. to hear what the VR user hears)*	45
Duration in VR: *(e.g. how long the VR user has been using VR)*	13
Other: *(please specify any other information you would want to know about a VR user)*	7

Table 4.5: The frequencies to Survey 2's question investigating what information respondents would want, as a bystander, about a nearby VR user

That respondents are not bothered or felt isolated due to the current aesthetic design of VR headsets and occlusion of the VR user's face is somewhat surprising. Prior works have speculated that the barrier the current aesthetic design of VR headsets creates between a VR user and bystander (e.g. a lack of eye contact, reduced ability to see the VR user's facial reactions) deter some bystanders from interacting with a VR user [83, 75] and works have explored the design of displays to provide a *"transparent HMD"* to mitigate such issues [84, 75]. However, the results of these questions suggest that bystanders (mostly) are in fact not bothered by the obstructed view of the VR user's face and that this does not frustrate or bother them when around VR users generally.

4.5.3 Desired Information During Bystander-VR User Interactions

Table 4.5 summarises the counts of respondents desire to know, as a bystander, different types of information about a nearby VR user and their experience in VR. Each factor is discussed, in turn, below.

Visual Content

73 respondents wanted to see, as a bystander, what the VR user's visual content was (e.g. to see what the VR user sees). Survey 2's story data highlights the benefits of access to such information within the stories describing scenarios where a bystander guides a user through

a VR experience (Section 4.4.4). Furthermore, prior work has established the social benefits of broadcasting a VR user's view in a manner which allows a bystander to observe and react to the VR user's in-VR actions [137, 138, 139].

Awareness of Reality

69 respondents wanted to know what awareness the VR user had of their surrounding environment (e.g. was the VR user aware of their co-presence). This point makes sense as the results of Chapter 3 and Survey 2's story data highlight that bystanders are often cautious around VR users due to uncertainty over whether the VR user knows they are co-present, or concern they will scare or surprise the VR user when interrupting them. However, situations can arise where a VR user, unbeknownst to the bystander, is aware of a bystander's co-presence (e.g. having overheard the bystander enter, having seen the bystander whilst in a passthrough view [92, 17], or being alerted of their co-presence through a bystander awareness system [6]). This, in turn, switches the power imbalance which can be created due to differing levels of bystander-VR user awareness (Section 4.4.5) to be in favour of the VR user who might take advantage of the bystander's unaware state to intentionally scare or collide with them. If, however, the bystander was prompted regarding the VR user's awareness of them [78] then the risk of such abuses could be mitigated against.

Interruptibility

61 respondents wanted to know the *"interruptibility"* of the VR user (e.g. did the VR user want to be disturbed while in VR). While Chapters 3 and 4 show that bystanders are comfortable interrupting VR users without this information, they also show that bystanders are conscious of this interruption. Most frequent was bystander concern of accidentally surprising or scaring the VR user being interrupted. However, some participants in Experiment 1 said they would not interrupt a VR user unless their reason was urgent as they did not wish to disrupt the user (who they assumed would prefer not to be disturbed while in VR). A similar result has also been noted by George et al in prior work [10]. Such bystander sentiment motivates the need systems to exist which relay a VR user's *"interruptibility"* to bystanders. Gottsacker et al. proposed attaching LEDs onto a VR headset as *"activity cues"* to relay such information [82] and greater than half of Survey 2's respondents expressing interest in such systems further reinforces their continued development and exploration in future works.

Aural Content

45 respondents reported wanting to hear, as a bystander, the VR user's auditory content (e.g. to hear what the VR user hears). While more respondents expressed interest in accessing the *Visual Content* of the VR user this preference toward visual information over auditory is perhaps explainable due to the visual-dense nature of VR as a medium [37, 66]. It should also be noted that additional auditory content could interfere with a bystander's ability to engage effectively in a verbal interaction with a VR user, potentially exacerbating the problems reported by some respondents in Survey 2 (Section 4.4.4) with problematic verbal bystander-VR user interactions.

Duration in VR

14 respondents wanted information on how long a VR user had been using a VR for. This is substantially fewer than were interested in the other types of metadata information (e.g. *Visual Content, Interruptibility, Aural Content*) respondents expressed interest in accessing above. And so while prior work has establish some interest in systems to manage and moderate VR usage [72] it is likely that such features will be of interest to specific types of individual (e.g. a parent wanting to manage their child's use of a VR device [140]) rather than a general bystander near a VR user.

Respondents "Other" Responses

There were 5 *"Other"* responses provided. Of these 2 said nothing of value (e.g. *"No suggestion"*). 2 of the responses suggested system be developed to allow bystanders to directly interact with the VR user's virtual environment to help guide a user during an experience, *P20: "A system to let me give hints/tips about the VR experience, to highlight points of interest"*. The remaining response suggested a system be developed to visualise the VR user's range of movement/motion within a physical environment, *P50: "Something to show their [the VR user's] range of motion/movement (and how much they are likely to move)"*

4.5.4 Comments About Bystander-VR User Interactions

Respondents provided 58 responses to the optional, open text question asking if they had any feedback or comments they wished to make regarding bystander-VR user interactions more generally. Of these 7 responses said nothing of value (e.g. *"No comment"*). Themes identified from the remaining 51 responses follow.

Impediments Encountered While Interacting

22 responses gave examples of problematic interaction scenarios which the respondents used to demonstrate impediments they had experienced during bystander-VR user interactions. 13 responses concerned problematic verbal interactions between a bystander and VR user, *P12: "A big problem with communication is that the vr user has a hard time hearing bystanders"*. This is similar to the *"Impediments Encountered During Verbal Bystander-VR User Interactions* theme in story data (Section 4.4.4) where evidence of bystanders' difficulty verbally interacting with VR users was reported. The remaining 9 responses concerned problems bystanders faced when sharing the same physical space as a VR user, *P94: "Moving around them [the VR user] is legitimately dangerous"*. This is similar to the *Managing the Physical Space in Which VR is Used* themes identified in the story data (Section 4.4.6).

Bystander Discomfort Interrupting a VR User

11 responses concerned bystanders discussing the discomfort they felt when they had to get the attention of and interrupt a VR user. All summarised the bystander's concern they would unintentionally surprise or scare the VR user being interrupted, *P40: "Its not comfortable when interrupting the VR user when they don't know you're there in case you scare them accidentally"*. These comments are similar to the results seen in Chapter 3 where participants expressed similar concerns regarding the interruption of VR users and a desire to minimise such feelings of surprise/scaring when interrupting a VR user. Similarly, the comments are similar to Survey 2's story data where respondents who used both verbal and physical contact when interrupting a VR user gave the rationale that they wanted to comfort/reassure the VR user being interrupted (Section 4.4.4).

The Non-Problematic Nature of Bystander-VR User Interactions

Not all the responses commented on perceived problematic elements of bystander-VR user interactions. 18 responses featured respondents stating that they did not believe interactions between bystanders and VR users to be problematic at all. Instead, these respondents suggested that it *P36: "it feels the same to interact [with or without VR]"* and stressed that bystander-VR user interactions were *P65: "not an issue"*. Such comments do fit with the results seen previously in this thesis. For example, Survey 1 indicated that bystanders are comfortable interrupting known VR users irrespective of setting (highlighting the introduction of VR alone does significantly alter social norms [113]). Some participants in Experiment 1 expressed similar sentiments when performing an interruption in practice. Finally, the results of Survey 2 also show respondents report low levels of frustration and high levels of comfort during bystander-VR user interactions. However, it should also be noted that throughout Chapters 3 and 4 many impediments on individuals ability to partake in a bystander-VR user interaction effectively have been identified. Additionally, the works of Chapters 3 and 4 have demonstrated the risk to a VR user's safety of being around a (malicious) bystander they are unaware of. Therefore, while some may not perceive bystander-VR user interactions to be particularly problematic, the need to develop awareness systems to facilitate these interactions remains pertinent.

4.6 Survey 2: Discussion

4.6.1 Bystander-VR User Interactions and Impediments

Survey 2 provides an overview of commonly occurring in-the-wild bystander-VR user interactions, attitudes towards these interactions, and impediments encountered during them.

Most of the stories collected described bystander-VR user interactions occurring within a home setting, between known individuals, involving *"verbal communication only"* or *"verbal communication and physical contact"*. That both verbal communication and physical contact were both used often when interacting reinforces the findings of Chapter 3 which indicated bystanders are comfortable and willing to use both to interact with known VR users. Survey 2 also found that most bystander-VR user interactions could be categorised as being either a *Coexisting, Demoing* or *Interrupting* interaction. The majority (79 out of 100) of stories reported some type of *Coexisting* interaction, reinforcing that bystanders and VR users often share the same space and that they often interact.

While respondents reported they were generally (mostly) comfortable and at most slightly frustrated during bystander-VR user interactions, numerous impediments to their experience when interacting were identified. Nineteen stories described interactions where the VR user partially/fully transitioned to a view of reality to accommodate their interaction with a bystander (Section 4.4.4). This was due to the VR user perceiving their interaction with the bystander as inadequate (either visually, aurally, or both) due to the occlusive nature of the VR headset being used. Similarly, twelve stories described instances where bystanders experienced difficulties verbally interacting with a VR user, where bystanders were required to shout to be heard or in some stories failed in their attempt to initiate a verbal interaction entirely (Section 4.4.4). These stories all provide empirical evidence highlighting the ineffectiveness of existing audio systems present in VR headset [120, 1] and further justify the need for VR headsets to be equipped with bystander awareness systems to support bystander-VR user interactions. In particular, these stories motivate a need to increase a VR user's aural awareness of their surrounding reality to improve individuals experience during verbal bystander-VR user interactions, the importance of which has also been noted by Ghosh et al [9] but has not yet been investigated by prior works.

Impediments also were identified during the *Demoing* interactions where twenty-four stories documented instances of new VR users requiring assistance controlling the VR experience and twenty-one stories scenarios where bystanders provided verbal instruction/guidance to the VR user (Section 4.4.4). The latter in particular was noted as a source of frustration for the bystander who due to an inability to highlight objects within the VR user's virtual environment when giving instructions reduced the process to one of trial-and-error. Both of these were sources of frustration for the bystander. However, systems to facilitate such interactions have been already explored for specialised applications in industry. For example, Ibayashi et al's Dollhouse VR proposed a tool for architects to allow a VR user to see a first-person view of a home while non-VR bystanders could modify its design in real-time [141, 142]. To facilitate communication between the VR user and bystanders Ibayashi et al developed a range of interaction techniques such as object highlighting and pointing tools. Exploring how similar tools could be developed to facilitate VR user and bystander interactions within the home is another direction future work, that is beyond the scope of this thesis, can consider.

4.6.2 When Bystanders Interrupt VR Users

Eight of the interruption stories reported instances of the VR user being surprised and/or scared due to the bystander's interruption (Section 4.4.4). This observation was not made during Experiment 1 (likely due to the VR user in the experiment knowing the interruption was going to occur). However, that an unexpected interruption would elicit this reaction from VR users is not surprising [143]. Furthermore, similar instances of VR users being surprised/scared by a bystander are reported in Dao et al's *"VR fails"* data set of online videos documenting *"failed"* interactions between bystanders and VR users [7]. These stories provide additional evidence justifying the creation of bystander awareness systems which, by preemptively notifying the VR user of a bystander's co-presence, can mitigate against the VR user being scared/surprised by the bystander.

Noteworthy also was bystander's decision to verbally interrupt the VR user (occurring in sixteen of the twenty-one interruption stories). This, combined with the difficulties reported in some stories experienced during verbal bystander-VR user interactions (Section 4.4.4), further affirms the need to develop awareness systems to facilitate verbal bystander-VR user interactions. Meanwhile, the use of physical contact when interrupting was less prevalent (occurring in nine of the twenty-one interruption stories) than was observed in Experiment

1. This, however, may be attributable to differences in the environments individuals were using VR within [94, 144, 145], the application in use by the VR user, individual preferences, etc. For example, in Experiment 1 the room in which the experiment was conducted was significantly more open/empty than a typical living room environment [144] and so bystanders may have felt more confident/able to approach the VR user and make physical contact. However, in a domestic environment the bystander may not have such affordances (e.g. the physical space such that the bystander is unable to approach the VR user) leaving a verbal interruption from distance the bystander's only method of interrupting.

4.6.3 Bystanders Position of Power Over Unaware VR Users

The need for bystander awareness systems is further exemplified by an overarching theme throughout several stories where bystanders are in a position power over the VR user. This occurs due to differing levels of awareness between the bystander and VR user (e.g. the bystander is aware of the VR user's co-presence whereas the VR user is unaware of the bystander's). Although some stories highlight that many bystanders act responsibly when in this position (e.g. often taking measures to ensure both their own and the VR user's safety (Section 4.4.6)), others show how bystanders may act maliciously and take advantage of the VR user's unaware state (e.g. physically pushing an unsuspecting VR user (Section 4.4.5)). These behaviours are similar to those seen in Experiment 1 where interrupting bystanders improvised a novel, unconventional interruption strategy which exploited the VR user's lack of awareness of their surrounding reality (Section 3.6). However, unlike Experiment 1, where participants cited only good intentions were behind their actions, the stories collected in Survey 2 hint towards how malicious bystanders might take advantage of the unaware nature of VR users.

For example, twelve stories contained bystanders taking advantage of an unaware VR user with actions ranging from teasing the VR user to pushing an unaware VR user (Section 4.4.5). Such behaviours are more malicious than the *"playful interruptions"* seen in Experiment 1. Furthermore, prior works have discussed the risk of an unaware VR user's personal possessions being stolen by malicious bystanders [11], or even the potential for a bystander to force an *"accidental VR fail"* to occur [7] (e.g. placing an object in the VR user's path and then filming their collision with it). Such risks to a VR user's safety highlights the need for VR headsets to be equipped with bystander awareness systems to protect VR users from (potentially malicious) bystanders in their surrounding environment.

This need to protect VR users through bystander awareness systems is reinforced by two stories which reported bystanders unsolicited filming of a VR users (Section 4.4.5). While some instances of a bystander filming a VR user will be consensual, these stories highlight how bystanders have the capacity to capture/share videos of an unaware VR user without their consent. Bystanders might also simply observe a VR user's activity (a story type not likely captured by Survey 2 due to the one-sided nature of the interaction). While awareness systems can assist with the latter (e.g. notifying the VR user that someone is there) these systems often do not inform the VR user of a bystander's actions. As such malicious bystander actions may occur even when the VR user has been notified of bystander's co-presence (e.g. if a VR user is notified of co-presence using a temporary text notification). This suggests the need for awareness systems to react to the actions of bystanders (e.g. recognising when a bystander takes out a smartphone and appears to film the VR user) and respond according (e.g. inform the VR user of the bystander's actions). The integration of social signal processing sensing [146] into the design of bystander awareness systems is one approach to achieve this which future work, beyond the scope of this thesis, could explore.

4.6.4 VR Users Position of Power Over Bystanders

It is not always the VR user who is the unaware individual within a bystander-VR user interaction. Instead, situations can arise where the VR user is in a position to exploit the co-located individual. The *"Bystander Becomes a Haptic Proxy for the VR User"* story (Section 4.4.7) highlights sexual activities are one such scenario. Here, mutual trust is required between the VR user and the co-located individual (the proxy person), however, it is unclear where the line between fun and abusive, healthy and unhealthy is drawn. What if the proxy person is reduced to a placeholder for the VR user's fantasies [78]? What if this facilitates unhealthy sexual relationships where the proxy person is reduced to a means of pleasure of the VR user? While the story described by the respondents was a consensual experiences for those involved currently, one can easily envision scenarios where this use of substitutional reality is taken to unhealthy and exploitative extremes [107, 108].

Fundamentally then, exploitation and abuse is possible from both parties, however the stories captured by Survey 2 suggest bystanders currently have more power, and assume more responsibility, over the VR user. However, it is worth reflecting that the snapshot captured by Survey 2 is of current behaviours around predominantly occlusive VR headsets, and one can expect this power balance will shift over time with new behaviours emerging, in-part enabled by the bystander awareness systems studied by this thesis [78]. As such, future work, that is beyond the scope of this thesis, should be continually reflective of such changes and further insights will need to be captured as these changes occur. To this end, Survey 2 demonstrates that a story-driven methodology can reveal novel insights into user behaviour in this context and so is recommended as one possible methodology future works might employ.

4.7 Conclusions

Through a story based survey, Survey 2, this chapter investigated how interactions occur between bystanders and VR users in-the-wild. The survey was designed to obtain empirical evidence of bystander-VR user interactions in real world, everyday environments to investigate the purpose of these interactions, how they are accomplished, attitudes towards them, and what impediments are experienced when interacting.

The results of Survey 2 reveal most bystander-VR user interactions can be categorised as into one of three high level interaction types: *Coexisting, Demoing*, or *Interrupting*. They also outline numerous impediments encountered when bystanders and VR users interact including the need of some VR user's to partially/fully transition to reality to facilitate their interaction with a bystander, further justifying the need for systems to be developed to better support VR users interaction with bystanders. Additionally, Survey 2 demonstrates the important role bystanders play when around a VR user (e.g. moderating the VR user's experience by intervening to save the VR user from potential harm through an accidental collision with reality). However, Survey 2 also demonstrates that bystanders will exploit their position of power over a VR user, further justifying the need for VR headsets to be equipped with bystander awareness systems as a safety feature for VR users.

Survey 2, combined with the results of Chapter 3, provide an understanding of the context of how bystander and VR users interact, and what impediments are encountered during interactions. In achieving this, Survey 2 also obtains empirical evidence of in-the-wild bystander interruptions of VR users reaffirming the findings of Chapter 3.

The results of Chapters 3 & 4 can therefore be used to answer **Research Question 1** and **Research Question 2** as follows:

Research Question 1: *When bystanders interrupt a VR user...*

- **1.1.** *how do they enact interruptions?*
- **1.2.** *what factors impact comfort and willingness to enact these interruptions?*

Given the results of Survey 1, Experiment 1 and Survey 2, the answer to Research Question 1 is that most bystanders are comfortable, and willing, to interrupt a known VR user using verbal interactions and/or physical contact. Often, bystanders will use verbal interactions and physical contact together when interrupting: first attempting to verbally inform the VR user of their co-presence then following up with physical contact to relay their location to in the surrounding area to the VR user.

The biggest identified influence on a bystander's comfort when interrupting was their relationship to the VR user which also influenced how they chose to interrupt the VR user. While bystanders indicated they are comfortable interrupting a known VR user using verbal interruption and/or physical contact, when interrupting an unknown VR user most were only comfortable using verbal interruptions from distance. The VR user's application in use was also reported to have some influence on how bystanders chose to interrupt, with bystanders indicating that a room-scale VR application (involving a VR user moving unpredictably around a physical space) would deter the use of physical contact and increase the reliance on verbal interruptions from distance. The setting of the interruption, meanwhile, was reported as having little to no influence on bystander's comfort interrupting and choice of interruption approach.

Research Question 2: *When bystanders and VR users interact...*

- **2.1.** *what is the context of the interaction?*
- **2.2.** *what impediments are encountered when interacting?*

Given the results of Survey 2, the answer to Research Question 2 is that most bystander-VR user interactions can be categorised as into one of three high level categories: Coexisting, Demoing, or Interrupting. Interactions between bystanders and VR users were reported as occurring often and involve both verbal exchanges and physical contact.

Numerous impediments were identified as occurring during bystander-VR user interactions. When bystanders interrupt VR users, multiple instances were reported of the VR user being scared/surprised by the bystander's interruption/co-presence. When bystanders demonstrate VR, issues arise with guiding the VR user through the experience and unfamiliarity with the controls and VR conceptually. When bystanders and VR users co-exist, a range of impediments were reported including bystanders attempts to initiate a verbal interaction with a VR user often being missed. Some VR users, meanwhile, reported partially or fully transitioning to reality to accommodate their interaction with a bystander (e.g. removing headphones to facilitate a verbal exchange). Bystanders also often report a sense of obligation to prevent accidents from occurring with the VR user (e.g. preventing the VR user from colliding with nearby objects or people). Significant also was the collection of empirical evidence where bystanders utilised the VR user being unaware of their co-presence to create a novel interruption. However, it should be noted that despite being down with seemingly humorous intentions in our studies these interruptions could be experienced as abusive or exploitative when around a malicious bystander.

4.7.1 The Subsequent Chapters of the Thesis

The results of Chapters 3 and 4 highlight the potential benefits of equipping VR headsets with bystander awareness systems to automatically increase a VR user's awareness of bystanders. Despite many individuals stating they were comfortable and not frustrated during bystander-VR user interactions, the results of Chapters 3 and 4 demonstrate numerous stories where these interactions are impeded upon and/or highlight the risks posed to an unaware VR user when around a malicious bystander. The use of bystander awareness systems can alleviate the impediments experienced when bystanders and VR users interact and reduce the risk of VR users being taken advantage of by malicious bystanders [6, 9]. The subsequent chapters of this thesis address some of the open challenges regarding the design of these bystander awareness systems identified by the literature review of this thesis (Chapter 2) and findings of Chapters 3 and 4.

Chapter 5 investigates the design of awareness systems to inform a VR user that a bystander is co-present. The findings of Chapters 3 and 4 demonstrated the importance of such systems to mitigate against the risk of an unaware VR user being the target of a malicious bystander. However, as discussed in the literature review of this thesis (Chapter 2) it is unknown what impact withholding the bystander's identifiable information and position from the VR user has when notifying the user of bystander's co-presence. Therefore, Chapter 5 presents Experiment 2 which was designed to investigate the impact of withholding this information when notifying a VR user of bystander existence.

Chapter 6 investigates the design of awareness systems to facilitate a verbal bystander-VR user interaction. As demonstrated by the findings of Chapters 3 and 4, verbal interactions between bystanders and VR users are often impeded upon due to the VR user's use of a VR (e.g. not hearing an attempt to initiate a verbal interaction because of the experienced immersive soundscape). Therefore, Chapter 6 presents Experiments 3 and 4 which were designed to investigate if a VR user's aural awareness could be increased by manipulating their experienced in-VR audio to facilitate a verbal bystander-VR user interaction.

Finally, Chapter 7 investigates how a VR user's awareness needs might vary during an interaction with a bystander. The literature review of this thesis identified that, at present, we lack a holistic understanding of how disparate works on bystander awareness might be brought together into cohesive systems to provide the *"right"* awareness to the VR user, and of how VR users will actually use awareness systems in practice. Therefore, Chapter 7 presents Experiment 5 which was designed to investigate how VR users would use a set of bystander awareness systems (informed by the literature review of this thesis and findings of Chapters 5 and 6) to increase their awareness of a bystander across a range of bystander-VR user interaction scenarios (informed from the findings of Chapters 3 and 4).

Chapter 5

Bystander Awareness Systems Without Identifiable / Positional Information

5.1 Introduction

The results of Chapters 3 & 4 reinforce the benefits of bystander awareness systems to support a user's use of VR. For example, without such systems VR users are at an increased risk of a malicious bystander's actions (e.g. intentionally being scared or pushed by a bystander they are unaware of, etc). Furthermore, from a usability standpoint, without these systems a VR user's potential interaction with a bystander is limited and inadequate [6, 9]. Any interaction between the bystander and VR user is unidirectional where the onus is entirely on the bystander to initiate any interaction (assuming the VR user is unaware of the bystander's existence and has not been somehow alerted to it through some accidental means).

Such issues are addressed when a VR headset is equipped with a bystander awareness system to notify the user of a bystander's existence [6, 9, 72]. By informing a VR user of a bystander's existence, the potential for a bidirectional interaction is created where either the VR user (notified of any co-presence) or the bystander can initiate an interaction with the other [6]. Furthermore, by providing the VR user with this increased awareness, the risk of a bystander maliciously exploiting the VR user is mitigated as bystander's advantage (of the VR user being unaware of their co-presence) is reduced/eliminated. Yet, as highlighted by Chapter 4's discussion, and in the literature review of this thesis (particularly Section 2.9), there remain open questions regarding the design of these bystander awareness systems to automatically notify a VR user of a bystander's existence.

Significant, is that it remains unknown what impact withholding a bystander's identifiable information and position from the VR user has when notifying them of a bystander's existence. If VR users are comfortable without information about either then this suggests that simple awareness system designs (e.g. anonymous text notifications, audio alerts, etc) may be sufficient to notify VR users of bystander existence. If, however, VR users are uncomfortable with the absence of either then more sophisticated and informative designs (e.g. designs which relay the bystander's identity and position continuously in real-time) will be required.

This chapter describes an experiment, Experiment 2, which investigated the impact of notifying a VR user of a bystander's existence using awareness system designs which are: anonymous (e.g. containing no identifiable information about the bystander), and relay varying amounts of positional information about the bystander. The goal of this experiment was to establish the impact of withholding identifiable information and positional information about a bystander when notifying a VR user of a their existence. The third research question of this thesis aims to address this by asking:

Research Question 3: *When notifying a VR user of bystander existence what is the impact of withholding...*

- **3.1.** *identifiable information about the bystander from the VR user?*
- **3.2.** *the bystander's position from the VR user?*

5.2 Experiment 2: Design

An experiment was conducted to investigate the design of awareness systems to automatically notify a VR user of a bystander's existence. The experiment was designed to investigate the impact of withholding: (1) identifiable information about the bystander, and (2) the bystander's position, when notifying the VR user of bystander existence. To investigate this four bystander awareness system designs (outlined in detail in Section 5.2.1) were developed using two modalities (two visual and two audio approaches). All were anonymous (e.g. containing no identifiable bystander information) and relayed varying amounts of positional information about the bystander to the VR user. The four bystander awareness systems were evaluated in two task contexts: a game task and a video watching task (outlined in detail in Section 5.2.2). Participants' sense of presence and their perceived usability of each awareness system was captured. A post-hoc semi-structured interview was conducted to elicit participant feedback on the designed awareness systems and, more generally, on their attitudes towards the information content of bystander awareness systems.

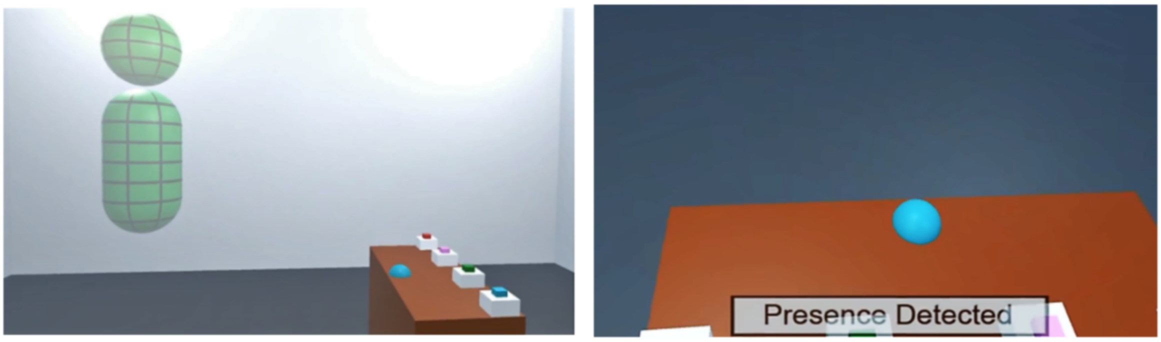


Figure 5.1: Experiment 2's visual awareness systems (shown during the game task). Left: *Avatar*. Right: *Text Notification*

5.2.1 Design of the Bystander Awareness Systems

The design of the four bystander awareness systems was derived from the findings of prior works. An overview of the awareness systems is provided in Table 5.1. The four developed awareness systems were:

- ***Text Notification:*** A temporary text notification (Figure 5.1) was displayed, in front of the VR user, for four seconds informing them of a bystander's entry (*"Presence Detected"*) or exit (*"Presence Left Area"*) from the surrounding environment [88, 9, 19].
- ***Avatar:*** An humanoid, semi-transparent avatar (Figure 5.1) displayed within the VR user's virtual environment mapped 1-to-1 in real-time with the bystander's position relative to the VR user [21, 20, 9, 24].
- ***Audio Notification:*** An audio equivalent of *Text Notification* where a beep sound effect played for one second to notify a VR user of a bystander's entry/exit from their surrounding environment [9, 56, 19]. Two tones of beep were used to uniquely signal entry/exit.
- ***Sonar Radar:*** A continuous beeping sound effect where the frequency/intensity of beeps conveyed the bystander's proximity to the VR user. When the bystander was less than 1.0m from the VR user, the beeps occur at 160 beats per minute (BPM). Distances between 1.0m and 2.0m at 80 BPM, and distances greater than 2.0m at 40 BPM. [147, 148].

Awareness System	Description	Modality	Persistence	Positional Information	Examples
Text Notification	A temporary text notification displayed for five seconds to notify of bystander entry/exit from the surrounding environment	Visual	Discrete	None (bystander within detectable distance)	[88, 9, 19]
Avatar	A humanoid avatar with a 1-to-1 mapping of the bystander's position in the surrounding environment relative to the VR user	Visual	Continuous	1-to-1 mapping of the bystander's position	[9, 21, 20, 24]
Audio Notification	A temporary audio alert to notify of bystander entry/exit from the surrounding environment	Aural	Discrete	None (bystander within detectable distance)	[9, 56, 19]
Sonar Radar	A beeping audio alert where frequency and intensity of beeps conveys the proximity of the bystander relative to the VR user	Aural	Continuous	Proximity of bystander	[147, 148]

Table 5.1: A summary of the design characteristics of the bystander awareness systems used in Experiment 2.

The Extent to Which Positional Information Was Varied

To investigate the impact of withholding a bystander's identifiable information from the VR user all of the awareness systems were designed to be anonymous. To investigate the impact of withholding the bystander's position from the VR user, the awareness systems were designed to relay varying amounts of positional information about the bystander to the VR user. To achieve this, the awareness systems were designed to vary by relaying:

- ***No Positional Information:*** The VR user is told a bystander is nearby without any indication of where (*Text Notification* and *Audio Notification*)
- ***Proximity Information Only:*** The VR user is only informed of the bystander's proximity from them (*Sonar Radar*)
- ***Full Positional Information:*** The VR user is shown a 1-to-1 mapping of the bystander's position relative to their own (*Avatar*)

The Choice of Bystander Awareness System Designs

Text Notification and *Audio Notification* were included as discrete, visual/audio approaches which contain no positional information about the bystander. Functionally these represent, visually and aurally, the minimal amount of information required to inform a VR user of a bystander's existence [6, 9]. *Sonar Radar* was included as a continuous, aural approach which relayed an approximation of the bystander's proximity to the VR user. This design was chosen as it is a widely known method of signalling the proximity between two objects [147, 148] and so was an approach easily explained to and understood by the experiment's participants (e.g. *"the faster the beeps, the closer the bystander is to you"*). Finally, the

Avatar was included as a continuous visual approach which relayed the exact position of the bystander relative to the VR user in real-time (e.g. a 1-to-1 mapping of the bystander's position onto the avatar's position). An avatar was chosen to relay this because it is the most prevalent method of notifying a VR user of bystander existence in the literature (e.g. [21, 24, 9, 6, 20]). A summary of the designed bystander awareness systems is provided in Table 5.1.

Implementation Details

A Microsoft Kinect 2.0 [149] was used to detect and track the bystander in real-time. Upon detection of the bystander, the awareness system being evaluated was triggered to inform the VR user of bystander existence. For the discrete approaches (*Text Notification* and *Audio Notification*) this triggered the corresponding *"Presence detected"* notification signalling that a bystander had entered, and was detected within, the surrounding environment. For the continuous approaches (*Avatar* and *Sonar Radar*) this triggered the corresponding approach and mapped the detected bystander's position, relative to the VR user, onto the awareness system in real-time. Upon detection of the bystander's exit from the surrounding environment (e.g. the Kinect sensor losing track of the bystander) the discrete approaches triggered the corresponding *"Presence left area"* notification while the continuous approaches simply removed the awareness system from the VR user's virtual environment.

5.2.2 Study Design

The experiment constituted of two tasks designed to recreate the affordances and visual/aural demand of home VR entertainment: a game task, and a video watching task. This provided two usage scenarios requiring high levels of attention demand and engagement from the VR user, which would consequentially stress the usability of the awareness systems being evaluated.

Each task had five conditions: one for each of the four bystander awareness systems and a baseline (no awareness system) condition. The condition order was counterbalanced using a five condition balanced Latin square approach. Task order was alternated every participant (e.g. eight did the game then video task, seven did video then game task).

Experimental Tasks

Both tasks were designed to be fixed, standing, experiences where users predominantly faced forwards. This ensured, by design, participants faced the direction of the room's door which the experimenter, acting as the bystander, entered from before walking a predetermined route around the room before exiting via the same door. This approach also ensured participants faced the direction the *Avatar* condition would appear in and is an approach often used by prior works to ensure an awareness system being evaluated is seen by participants during an experiment (e.g. [6, 20, 21, 22]). A description of each task follows:

- ***Game Task:*** Participants played an arcade-style Simon-like [150] button pressing game for sixty seconds. The game worked by randomly selecting a target colour from four colour options and tasked the player with pressing the button, represented as physical push buttons in the VR scene (Figure 5.1), which matched the target's colour. One point was gained for every correct button press and one point lost for every incorrect press. This game design was chosen as a simple, yet effective, way of creating of creating engaging gameplay [54] and because its design fit the criteria of a standing experience where the player's focus faced predominantly in a single, controlled, direction.
- ***Video Watching Task:*** Participants watched a one of five, sixty second videos. Five advertisement videos were chosen as the videos watched by participants (two fashion videos and three video game trailer videos). Participants pressed a button to start the video and were required to provide no other input.

5.2.3 Questionnaire Measures

A questionnaire was designed to evaluate the impact of the bystander awareness systems on the user's sense of presence in VR, and the perceived usability of the awareness systems. All questions used a 7-point Likert scale.

- ***Sense of Presence Questions:*** presence was evaluated using (1) the *"Sense of Being There"*, and (2) the *"Involvement"* subset of the IPQ questionnaire [46].
- ***Usability Questions:*** usability was evaluated using four Likert scale questions (1=strongly disagree, 7=strongly agree) that asked to what extent participants agreed the awareness system (1) *"was useful"* and to what extent they were (2) *"comfortable"*, (3) *"distracted by the awareness system"*, and (4) *"aware of reality"*.

At the end of the experiment a semi-structured interview was conducted to elicit feedback from participants regarding the design of the awareness systems and their attitudes, more generally, towards how they bystander awareness expected to be provided. Participants were asked to: (1) discuss their preferred awareness system and why, (2) discuss the impact (if any) of withholding identifiable and positional information about the bystander within the awareness system's design, (3) to compare and give their opinions on the audio and visual approaches, and (4) if their preferred awareness system changed depending on the task being performed (i.e. watching something vs playing a game).

5.2.4 Apparatus

A Microsoft Kinect 2.0 was used to detect the bystander, track their position, and map the information to the virtual environment in real-time. The Kinect was positioned on a table which the VR user stood behind. The difference in the position of the Kinect and the VR user was offset within the VR user's application such that the avatar of the bystander in VR accurately mapped to the bystander's actual position in reality. A HTC Vive [91] was used to conduct the experiment. Participants wore a pair of consumer Sony on-the-ear headphones during the experiment.

5.2.5 Procedure

Upon arrival the experiment's purpose was explained and a consent form and demographic questionnaire given to the participant. Participants were told the experiment would be investigating the design of awareness systems to automatically notify a VR user when someone entered the room. It was explained that the participants would experience four awareness systems in two application contexts (a video game and video watching task) and that the experimenter would pose as a known bystander who entered the room (e.g. a friend they lived with). The controls used within the VR applications were then explained. The participant was then instructed where to stand during the study and shown (if required) how to put on and fit the VR headset. The experimenter then setup the first condition to be evaluated and stood outside of the room at the door (beyond the Kinect sensor's detectable range). The door was left open to avoid the noise disruption caused by its opening/closing. Participants were then instructed to start the application.

Once the participant started the application, the experimenter waited twenty seconds before entering the room and walking one of five set routes around it. All routes started and ended at the door of the room and included a range of distances from 2.5 metres to 0.5 metres away from the VR user. The experimenter was co-present for twenty-five seconds before exiting the room. Routes walked by the experimenter were counterbalanced using a five condition balanced Latin square approach.

When the participant's task in VR ended, they removed the VR headset and completed a questionnaire while the experimenter setup the next condition. This process was repeated until all of the conditions were evaluated across both tasks. A semi-structured interview was then conducted to elicit feedback from participants regarding the design of the awareness systems and their expectations for increasing awareness of bystanders more broadly. The experiment took on average forty-five minutes to complete. Participants participation in the experiment was voluntary.

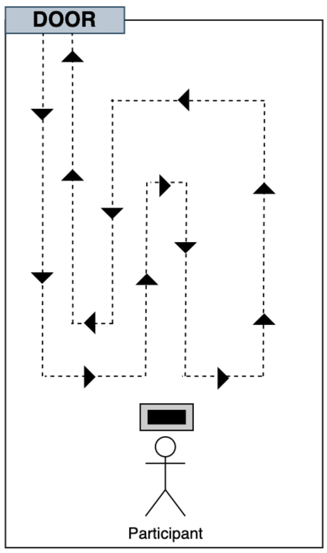


Figure 5.2: A sketch of the room in which the experiment took place. The participant stood behind a table with a Kinect on it. A dotted line maps one path walked by the experimenter during the experiment (arrows show the direction the path was walked).

5.3 Experiment 2: Results

5.3.1 Participants

Participants were recruited using social media and university mailing lists. 15 participants (5 female, 10 male) completed the experiment. Participants ranged in age from 20 to 36 years (M=25.10, SD=4.74). Participants were asked to indicate their prior experience with VR headsets using a 5-point Likert scale (1=none, 5=a lot), (M=2.80, SD=2.01). 7 reported they had at least *"a little (2)"* prior experience with VR.

5.3.2 Analysis

A Friedman test was used to find significant differences between factors and was followed by pairwise comparisons using Wilcoxon signed-rank tests with Bonferroni corrected p-values. Participants' interviews were coding using selective coding [121] where participants' statements were assigned emergent codes over repeated cycles with the codes grouped using a thematic approach. A single coder performed the coding and reviewed/discussed the coding with one other researcher. Two coding cycles were performed.

5.3.3 Usability Evaluation Results

The mean, standard deviation values and Friedman test results of the usability questions are summarised in Table 5.2. The results of Wilcoxon signed-rank pairwise comparisons are summarised in Table 5.2 also. Each usability question is discussed, in turn, below.

Game Task							
Usability	*(1) Baseline*	*(2) Text Notification*	*(3) Avatar*	*(4) Audio Notification*	*(5) Sonar Radar*	***Friedman Test***	***Wilcoxon Post-hoc (p<0.005)***
Comfort	5.00 (0.93)	4.53 (1.36)	5.27 (1.29)	4.73 (1.29)	4.40 (1.62)	*$\chi^2(4) = 5.87$, $p>0.005$*	N/A
Awareness of Reality	3.34 (1.64)	4.53 (1.15)	5.07 (1.18)	4.47 (1.02)	4.60 (1.36)	*$\chi^2(4) = 10.71$, $p>0.005$*	N/A
Distraction	2.57 (1.18)	4.40 (1.93)	3.73 (1.73)	3.73 (1.44)	4.20 (1.47)	*$\chi^2(4) = 7.35$, $p>0.005$*	N/A
Usefulness	3.07 (1.91)	5.07 (1.53)	5.07 (1.29)	4.67 (1.62)	4.33 (1.89)	*$\chi^2(4) = 14.90$, $p<0.005$*	*1-2, 1-3*
Video Watching Task							
Usability	*(1) Baseline*	*(2) Text Notification*	*(3) Avatar*	*(4) Audio Notification*	*(5) Sonar Radar*	***Friedman Test***	***Wilcoxon Post-hoc (p<0.005)***
Comfort	5.07 (1.24)	5.27 (1.18)	4.87 (1.09)	5.13 (1.15)	4.80 (1.22)	*$\chi^2(4) = 3.64$, $p>0.005$*	N/A
Awareness of Reality	3.67 (1.74)	3.87 (1.54)	4.40 (1.70)	4.13 (1.20)	4.93 (1.34)	*$\chi^2(4) = 5.85$, $p>0.005$*	N/A
Distraction	3.33 (2.21)	4.20 (1.90)	4.80 (1.76)	3.53 (1.59)	4.47 (1.71)	*$\chi^2(4) = 4.69$, $p>0.005$*	N/A
Usefulness	2.93 (1.69)	5.40 (1.74)	5.73 (1.12)	3.87 (1.71)	4.87 (1.54)	*$\chi^2(4) = 24.37$, $p<0.005$*	*1-2, 1-3, 2-4, 3-4*

Table 5.2: Experiment 2's mean (standard deviation) values, and significant differences, for the usability evaluation questions for the game and video watching task. Significant differences were only found in the *Usefulness* factor where the visual approaches were considered more useful than the baseline and aural awareness approaches.

Awareness of Reality

All of the conditions were reported as increasing awareness of reality compared to the *Baseline* condition, particularly in the game task. However, no significant differences between the conditions were reported as occurring in either task.

Comfort

All of the conditions were reported as being moderately comfortable in both tasks. No significant differences between the conditions reported as occurring in either task.

Distraction

All of the conditions were said to increase distraction from the VR application compared to the *Baseline* condition with 6 participants stating that the visual awareness systems were more distracting than the aural awareness systems. For the video task, the *Avatar* was the most distracting condition which 4 participants attributed to the avatar blocking the view of their video, *P1: "The last thing I want is someone standing in front of the TV screen"*. For the game task, the *Text Notification* was the most distracting condition which 5 participants attributed to the notification's placement obstructing the view of objects in the virtual environment being interacted with by the VR user, *P2: "[For the game task] Text was probably the worst as it was right in your face blocking your view of the game content and there was nothing you could do about it"*. However, no significant differences between the conditions were reported as occurring in either task.

Usefulness

The visual awareness systems were considered more useful than the aural awareness systems. Significant differences between the conditions were found to occur in both tasks. For the video task, four significant differences were found: between the *Baseline* and *Text Notification*, the *Baseline* and *Avatar*, the *Text Notification* and *Audio Notification*, and the *Avatar* and *Audio Notification*. For the game task, two significant differences were found: between the *Baseline* and *Text Notification*, and between the *Baseline* and *Avatar*.

5.3.4 Sense of Presence Evaluation Results

The mean, standard deviation values and Friedman test results of the sense of presence questions are summarised in Table 5.3. The results of Wilcoxon signed-rank pairwise comparisons are summarised in in Table 5.3 also.

No significant differences were reported as occurring for the *IPQ: Sense of Presence* and *IPQ: Involvement* questions in either task (Table 5.3). The *Avatar* condition scored lowest across both tasks, for both *IPQ: Sense of Presence* and *IPQ: Involvement* mean values, although was not found to be significantly different from the other conditions.

5.3.5 Participant Interviews

Withholding the Bystander's Position From the VR User can Create Discomfort

9 participants said they were comfortable being notified of bystander existence without any positional information (e.g. they were comfortable using either *Text Notification* or *Audio Notification*). However, 6 participants said being notified of bystander existence without being told the bystander's position relative to their own made them uncomfortable, *P5: "Knowing someone was there with no idea where felt a bit creepy. It made me wonder where you were in the room. I preferred the avatar which told me exactly where you were"*. Participants who expressed this sentiment said they were left feeling *P12: "in the dark"* when notified of bystander existence without positional information, and compared the experience to that of being in a pitch black room and told someone was in the room with them, *P12: "it's just*

Game Task							
Sense of Presence	*(1) Baseline*	*(2) Text Notification*	*(3) Avatar*	*(4) Audio Notification*	*(5) Sonar Radar*	***Friedman Test***	***Wilcoxon Post-hoc ($p<0.005$)***
IPQ: Sense of Being There	5.14 (1.36)	5.33 (1.30)	5.07 (1.61)	5.20 (1.28)	5.20 (1.60)	$\chi^2(4) = 1.27$, $p>0.005$	N/A
IPQ: Involvement	4.41 (1.69)	4.12 (1.43)	3.78 (1.57)	4.05 (1.55)	4.03 (1.65)	$\chi^2(4) = 0.95$, $p>0.005$	N/A
Video Watching Task							
Sense of Presence	*(1) Baseline*	*(2) Text Notification*	*(3) Avatar*	*(4) Audio Notification*	*(5) Sonar Radar*	***Friedman Test***	***Wilcoxon Post-hoc ($p<0.005$)***
IPQ: Sense of Being There	5.40 (1.25)	5.20 (1.42)	4.67 (1.62)	5.53 (1.15)	5.13 (1.26)	$\chi^2(4) = 2.62$, $p>0.005$	N/A
IPQ: Involvement	4.50 (1.78)	4.42 (1.68)	4.17 (1.54)	4.32 (1.68)	4.20 (1.65)	$\chi^2(4) = 0.77$, $p>0.005$	N/A

Table 5.3: Experiment 2's mean (standard deviation) values, and significant differences, for the sense of presence evaluation questions for the game and video watching task. Moderate presence levels were reported for all the conditions in both tasks.

a bit unsettling, like something out of a horror film, you know they are in the room with you but you can't see them and have no idea what they are doing or from which direction they might touch or approach you".

Of the 6 participants who were made uncomfortable by a lack of positional information about the bystander, all stated that *Text Notification* and *Audio Notification* were not suitable methods to be notified of bystander existence with. Additionally, all 6 participants considered the positional information relayed by the *Sonar Radar* to be insufficient also, as it provided only an approximation of the bystander's position rather than a 1-to-1 mapping, *P11: "I didn't know if you were to my left, right or straight ahead. It didn't really help or add anything to the experience"*. As such, all 6 participants said the *Avatar* was their preferred choice of awareness system because of its continuous, real-time, 1-to-1 mapping of the bystander's position relative to their own.

Withholding the Bystander's Identity and/or Position can Encourage VR Users to Exit VR

When discussing the design of the awareness notifications used in the study, 11 participants said they would likely *P1:"peek out from under the headset"* due to the insufficient information regarding the bystander's identity (11 participants) or position (6 participants). All participants who indicated they would use this *"peeking"* behaviour said their primary justification was to identify the bystander, *P1: "The notification tells me someone is there but not who and that's what I really need to know"*. Unsurprisingly, participants suggested that embedding identifiable information about the bystander into the awareness system would alleviate this need to peek, *P14: "[to reduce the need to peek] maybe include like a photo of the person inside the text notification or their face put onto the avatar"*

In addition to peeking to identify the bystander, 6 participants also said they would exit VR to locate the bystander if the positional information provided by the awareness system was insufficient, *P11: "[regarding the non-Avatar conditions] Even if I know who they are, I still want to know where they are, so I'd be constantly checking"*. Furthermore, 7 participants said there would likely be scenarios where upon exiting VR they chose not to return, instead opting to remain in reality to interact with the bystander, *P5: "So if I look out [of VR] and they [the bystander] start talking to me I'm probably just going to stay out of VR until the conversation is over"*.

Meanwhile, the 4 participants who stated they would not use such *"peeking"* behaviours said they were uninterested in who was there, where they were located, and what they wanted unless it related to them, *P4: "if they really want or need my attention they can just get it* *otherwise I can just ignore them"*. As such, these participants said they were comfortable being notified of bystander existence without identifiable or positional information about the bystander.

The Visual Approaches Were Preferred To Audio Approaches

Participants preferred the visual awareness systems over the audio approaches because they believed the visual approaches were: (a) more distinct/noticeable, and (b) more informative. For example, *Text Notification* was considered more noticeable than *Audio Notification* due to the *Text Notification* being more *P2: "in your face"* whereas the *Audio Notification* risked being masked by the in-VR audio of the application being used by the VR user. Meanwhile, the visual awareness systems were considered more informative than the aural approaches as they were believed to more clearly relay information content to the VR user, *P6: "with the visual ones its just easier to imagine how you could add more information easily, configure the text notification to include a photo of them [the bystander] or not... its also just easier to understand visually their [the bystander's] exact position relative to my own"*. Although, it is worth noting that 2 participants discussed how they perceived the *Sonar Radar* to be the most urgent condition and how they consequentially felt it would be best suited as a final safety alert for the VR user, *P3: "I thought the increase in intensity was good when someone gets up close and it starts beeping like crazy... I think it's a good warning"*.

The Risk of Awareness Systems Being Masked by Application in Use

For the audio awareness systems, 6 participants said they thought the in-VR audio of an application in use could easily be mistaken for the *Audio Notification* (or vice versa), *P15: "With the audio it's like when you think your phone goes off or makes a noise and it's actually something in the film that you mistake for your own phone"*. While these 6 participants felt the *Sonar Radar* was more aurally unique and distinctive, and therefore at less risk of being masked/missed, they still expressed concern that it could be mistaken for the audio of an application in use, *P15: "with the sonar there might be a delay in realising what it is, like you think its the application audio but then you go 'oh no wait that's a notification'"*.

For the visual awareness systems, 7 participants identified the *Avatar* at risk of either being mistaken as part of an application in use or simply being missed by the VR user, *P2: "So there's the problem of noticing its there [the avatar] because I wouldn't see it if it was behind me or I was looking in the other direction. Then I have to recognise what it is and not think its just part of the game."*. Reflecting on these comments, 5 participants said they wanted the ability to customise the avatar's aesthetic design to make it *P2: "more recognisable and* *distinct"*. These participants believed by customising the avatar they would be able to ensure it was *P13: "identifiable at a glance relative to the rest of the VR scene"* by ensuring it contrasted aesthetically with the presented VR experience. Finally, 7 participants felt that the *Text Notification*, due to its *P2: "in your face"* design, was at less risk of being missed, although acknowledged if a different design was used (e.g. a text notification with a different placement/urgency [88]) that it may be at risk of being missed also.

The Applications Tasks Were Too Similar to Warrant a Difference Response to the Awareness Systems

Participants did not consider the differences between the tasks to have a meaningful impact on their response to the awareness systems. Participants said as both tasks required the VR user to be stationary and primarily face in a single direction that the tasks were too similar to influence their responses, *P7: "I think those apps [the experienced tasks] are very similar so my opinion doesn't really change because of what I was doing"*, Instead, similar to the results of Experiment 1 (Section 3.6), 3 participants said that they would likely change their response had a room-scale VR application [34] been used instead. Specifically, these participants said they would favour/prioritise the *Avatar* over the other approaches due to increased risk to their safety posed in a room-scale VR context, *P8: "So if it was an app where I was walking around I'd only want the avatar so I didn't bump into the person. If it was the text pop up or the audio ones I just wouldn't feel confident walking around."*.

5.4 Experiment 2: Discussion

5.4.1 Peeking to Contextualise Insufficient Bystander Identifiable / Positional Information

The results of Experiment 2 show that some VR users in response to what they perceive as insufficient information to contextualise awareness of a bystander's co-presence (e.g. who they are, where they are located) will exit VR (i.e. by physically removing the headset or peeking out from under it) to obtain the absent desired information. Often, having obtained the absent information, the VR user will then immediately return to VR having unnecessarily interrupted their presence/immersion. This behaviour, termed *"peeking"*, highlights a limitation of bystander awareness systems which withhold too much information about the bystander from the VR user. Furthermore, this is a limitation which has been overlooked by prior works due to their focus on evaluating whether the designed awareness system is noticed by the VR user (e.g. can it successfully increase awareness of the bystander) and to what extent it alters the user's sense of presence in VR [24, 20, 9, 19, 87, 23].

Crucially then, is that prior works have not fully considered the implications of the information content a bystander awareness system relays to a VR user, and what subsequent impact this may have on the VR user's behaviour. Experiment 2 identifies one consequence overlooked by prior works. That is, some VR users if they lack sufficient contextualising information about the bystander will exit VR to obtain it. For example, many prior works have used anonymous avatar designs to notify a VR user of a bystander's existence [23, 9, 20, 24, 87, 21, 22, 18]. However, the results of Experiment 2 show that some VR users, in response to seeing an anonymous bystander avatar, may exit VR to identify who the bystander is only to then immediately return to VR. Similarly, prior works have considered haptic alerts [9, 56] to notify a VR user when a bystander is co-present. Again, the results of Experiment 2 show if notified of bystander existence with such an awareness system that some VR users may exit VR to identify the bystander or check the bystander's position relative to their own.

5.4.2 Formalising VR User "Peeking"

To define and summarise this *"peeking"* behaviour more formally, in the context of bystander awareness, a *"peek"* is defined to be a VR user initiated, temporary exit from virtuality to reality by either removing the headset, peeking out from under it, or switching to a full passthrough view (e.g. [92]). The emergence of such behaviours allows for the envisioning of scenarios where such peeks may likely occur. For example, consider what occurs when a bystander enters the room or surrounding area of a VR user. If the VR headset being used does not have a bystander awareness system then any awareness the VR user has of this bystander (assuming a well-fitting headset) is largely contingent upon them hearing real-world audio (e.g. footsteps, speech) over and above the existing immersive VR soundscape. Based on what they hear, they may: remain unaware of the bystander, become aware of an unidentified presence (e.g. by hearing footsteps) and peek to investigate who is there and/or where they are, or become aware of an identified presence (e.g. hear and recognise the voice of a speaking bystander).

However, if the VR headset does include a bystander awareness system then awareness of the bystander is contingent upon: (1) the headset detecting/capturing the bystander (e.g. if the bystander approaches from outside the headsets FOV they would go undetected), and (2) that the relayed bystander is noticed by the VR user within the virtual environment. In response to this the VR user may either: remain unaware of the bystander, or become aware of the bystander but lack sufficient contextualising information (e.g. not recognise who is there from the relayed information and want to know), or become aware of the bystander with sufficient contextualising information. Should a VR user be made aware a bystander is there but lack sufficient contextualising awareness of them then some VR users will inevitably resort to *"peeking"* to obtain this information.

After peeking the user will make a decision either to: (a) remain in reality to interact with the person, or (b) return to VR having temporarily, and unnecessarily, broken their presence/immersion. Ultimately, the VR user is making a decision regarding whether they want/need to remain in virtuality. This decision, if made whilst in reality, is high cost [151, 152] (in terms of disruption to presence/immersion and is a mental mode switch from virtuality to reality) because the VR user is effectively removed from virtuality to acquire the necessary information required to make their choice [94, 55, 6].

5.4.3 Resolving Peeks By Contextualising Bystander Co-Presence

The results of Experiment 2 indicate by embedding more information (e.g. identifiable information, a 1-to-1 continuous relay of the bystander's position) into any initial notification/presentation of bystander co-presence that this VR user *"peeking"* behaviour can be mitigated against. Prevention of this *"peeking"* behaviour requires sufficient information be embedded into any initial bystander awareness system to enable a VR user to make an informed decision regarding whether to exit VR to interact with the bystander or remain in VR. While prior works have established that bystander awareness systems can, to varying degrees depending on the approach taken, significantly decrease a VR user's sense of presence (e.g. [6, 20, 55, 21, 23]), the results of Experiment 2 demonstrate how VR users may break presence entirely if they perceive the awareness system to insufficiently contextualise the bystander's co-presence. Such breaks in presence can be considered a design failure of a bystander awareness system, particularly if its intention was to increase awareness while minimally disrupting the VR user's presence/immersion. Therefore, while embedding additional information to ensure *"peeking"* is mitigated against may slightly increase the disruption caused by a bystander awareness system [6, 55], the decision faced by the VR user - either to remain in virtuality or exit to reality - can, crucially, be made while the VR user is still (mostly) immersed in VR.

5.4.4 Additional Insights Regarding the Design of Bystander Awareness Systems

The results of Experiment 2 also provide various insights into the design of bystander awareness systems. First, the results show that participants preferred visual awareness systems which they perceived as more informative and useful than the audio approaches. Preferences, with similar justifications, towards visual bystander awareness systems (over audio and haptic approaches) have also been reported by Ghosh et al [9] in prior work.

Noteworthy also were comments made discussing the risk of awareness systems being missed by the VR user. Participants discussed the risk of this occurring to both visual and audio awareness systems. Aurally, participants discussed the risk of the *Audio Notification* being mistaken for the in-VR audio of an application in use (or vice versa). Visually, participants discussed the risk of the *Avatar* being mistaken for part of the VR application in use, or simply being missed because the VR user was looking in a different direction than one the avatar appeared in, a point also made by Medeiros et al [20].

Such comments highlight the need to ensure bystanders awareness systems are, by design, distinct enough to be noticed/seen by VR users. Similar findings have been reported in works on notifications design for ambient displays [153] where the guidance is given to *"make visuals distinct"* [154] to ensure specific content/notifications are seen by users. In the context of bystander awareness systems and VR, this can be achieved by ensuring there is sufficient contrast between the VR content and the awareness system, e.g. through aesthetic differences between of the awareness system and VR scene (e.g. McGill et al's photoreal avatar augmented into a VR environment [6]) or by forcing the VR user to engage with the awareness system (e.g. Rzayev et al's VR notification placement guidelines [88]).

5.4.5 The Influence of a Bystander's Position on a VR User's Awareness Needs

The two task contexts used in Experiment 2 were not considered by participants be sufficiently different to justify a change in participants' response to the awareness systems. As in the results of Experiment 1 (Section 3.6), participants suggested that a room-scale VR application [34] (e.g. one requiring the VR user to walk around a physical space rather than remain (mostly) stationary) would however likely change their response to the awareness systems. This was due to the perceived increased risk to the VR user's safety in this application context (e.g. an accidental collision between a VR user and bystander [7]). In this context, participants felt there would be an increased importance of knowing the bystander's position relative to their own (as the VR user) to avoid accidental collisions with the bystander. This, in turn, suggests that the proxemics of a bystander-VR user interaction may be a factor which influences a VR user' awareness needs whilst interacting. For example, a VR user may be comfortable without positional information if the bystander is located outside of the VR user's defined play area but want a continuous 1-to-1 mapping of any bystander's position inside of the play area [87].

5.5 Conclusions

Through a lab experiment, Experiment 2, this chapter investigated the impact of withholding identifiable and positional information about a bystander when notifying a VR user of a bystander's existence. The experiment was designed to evaluate and elicit feedback on the design of four bystander awareness systems which were anonymous and relayed varying amounts of positional information about the bystander.

Experiment 2's results reveal insights into the design of bystander awareness systems. Most significant, and most relevant for answering **Research Question 3**, was the identification of a *"peeking"* behaviour by some VR users in response to bystander awareness system designs they perceived to relay insufficient contextualising information about the bystander. This *"peeking"* behaviour occurs when a VR user temporarily exits VR, either by removing the headset, peeking out from under it, or switching to a full passthrough view, to obtain additional information about a bystander they have been made aware of. Such a response to the exposure of a bystander awareness system can be considered a failure of its design, especially if its intention was to increase awareness while minimising disruption to the VR user's sense of presence. The results of Experiment 2 identify that a lack of identifiable information about the bystander and a lack of positional information about the bystander will motivate some VR users to engage in this *"peeking"* behaviour. The results of Chapter 5 can therefore be used to answer **Research Question 3** as follows:

Research Question 3: *When notifying a VR user of bystander existence what is the impact of withholding...*

- **3.1.** *identifiable information about the bystander from the VR user?*
- **3.2.** *the bystander's position from the VR user?*

Given the results of Experiment 2, the answer to Research Question 3 is that while some VR users are comfortable being notified of bystander existence without any identifiable or *positional information about the bystander, others are not. Consequentially, VR users who are uncomfortable being notified of a bystander's existence with what they perceive as insufficient identifiable or spatial information about the bystander will exit VR to obtain this information. The prevention of such "peeking" behaviours necessitates that sufficient information be embedded into any initial notification or presentation of bystander co-presence, although what is considered sufficient varies across VR users (e.g. some are comfortable without identifiable bystander information whereas others are not). However, by providing a VR user with sufficient information about a bystander, an informed decision regarding whether to remain in VR or break presence to interact with the bystander can, crucially, be made by the VR user whilst still (mostly) immersed in VR.*

Chapter 6

Manipulation of In-VR Audio to Increase a VR User's Aural Awareness

6.1 Introduction

The previous chapter investigated the design of awareness systems to notify a VR user of a bystander's existence. However, this represents only a singular type of increased bystander awareness: informing the VR user that someone is there. This, in turn, represents only an initial step towards facilitating bystander-VR user interactions that does not fully encapsulate the potential awareness needs of a VR user. For example, the results of Experiment 1 and Surveys 1 & 2 showed verbal interactions occur frequently between a VR user and bystander, yet: (a) VR users often miss bystanders attempts to initiate a verbal interaction, and (b) some VR users during verbal interactions will partially or fully remove in-VR audio (e.g. removing headphones or reducing/muting the volume of the headset) to facilitate a verbal interaction. This highlights a different set of awareness needs experienced by VR users - to increase aural awareness of their surrounding environment. Consequentially, this requires a functionally different type of bystander awareness system, one which primarily increases aural awareness, compared to the awareness systems investigated in the previous chapter (which primarily sought to notify the VR user that a bystander was co-present). Yet, at present, no research has investigated how verbal bystander-VR user interactions might be facilitated through bystander awareness systems.

As highlighted in the literature review of this thesis (particularly in Section 2.4), recent works have demonstrated that in-VR audio can be manipulated (e.g. by removing sound effects and background music from a VR game [66, 60, 69, 155]) without significantly impacting the user's sense of presence in VR or enjoyment of the experience. This chapter attempts to apply these observations in the context of increasing a VR user's bystander awareness and describes two experiments which explored how in-VR audio might be manipulated, whilst minimally disrupting a VR user's sense of presence, to facilitate a verbal bystander-VR user interaction. The first experiment, Experiment 3, investigated a bystander awareness system which automatically increased/decreased in-VR audio volume to decrease/increase a VR user's awareness of a nearby sound events. The second experiment, Experiment 4, built on Experiment 3's results and investigated the effectiveness of automatically decreasing in-VR audio volume and of partially/fully removing of in-VR audio to facilitate verbal bystander-VR user interactions. The goal of these experiments was to establish effective methods of manipulating in-VR audio to facilitate verbal bystander-VR user interactions and to assess individuals' attitudes towards the approaches explored. The fourth research question of this thesis aims to address this by asking:

Research Question 4: How may in-VR audio be manipulated to facilitate verbal bystander-VR user interactions?

6.2 Experiment 3: Design

An experiment was conducted to explore the use of automatically increasing/decreasing in-VR audio volume to decrease/increase awareness of sound events in a VR user's surrounding environment. The experiment used a video watching task where participants experienced four conditions and were exposed to two sound events: a door knock (to increase awareness of) and a vacuum cleaner (to decrease awareness of). For each condition, participants' sense of presence in VR and awareness of the sound events was evaluated. Participants' preferences of the conditions experienced and general feedback was also captured.

6.2.1 Design of the Audio Manipulations

Four conditions were devised to investigate a VR user's aural awareness of sound events in their surrounding environment. Two of the conditions explored the existing audio systems present in VR headsets [1]: (a) headphones, and (b) the on-board, acoustically transparent audio system (where speakers are built into headset's headstraps to leave the VR user's ears uncovered during use to provide an increased aural awareness of the surrounding environment) [120]. Two of the conditions were designed as *"dynamic"* variations of these that automatically increased/decreased the volume of the in-VR audio experienced by the VR user to decrease/increase their aural awareness of sound events in their surrounding environment. The four conditions investigated were:

- ***On-board Audio:*** The on-board, acoustically transparent [120], audio system of the Oculus Go headset [156] used to conduct the experiment. In-VR audio volume remained at its starting value for the entirety of the condition. An existing audio solution present in consumer VR headsets [1], used as a baseline.
- ***Dynamic On-board Audio:*** A variation of *On-board Audio* which manipulated the in-VR audio experienced by the VR user by decreasing/increasing the application's volume to increase/decrease awareness of sound events in VR user's the surrounding environment.
- ***Headphone Audio:*** On-the-ear headphones plugged directly into the Oculus Go headset [156] used to conduct the experiment. In-VR audio volume remained at its starting value for the entirety of the condition. An existing audio solution present in consumer VR headsets [1], used as a baseline.
- ***Dynamic Headphone Audio:*** A variation of *Headphone Audio* which manipulated the in-VR audio experienced by the VR user by decreasing/increasing the application's volume to increase/decrease awareness of sound events in VR user's the surrounding environment.

On-board Audio and *Headphone Audio* were included as baseline conditions as they are audio systems present in current consumer VR headsets and both are reported to be regularly used by consumers [1]. The *Dynamic* variants of *On-board Audio* and *Headphone Audio* were designed to explore the manipulation in-VR audio by automatically increasing/decreasing the application's volume to increase/decrease awareness of sounds made in the user's surrounding environment. This audio manipulation was derived from similar automatic volume control/adjustment systems present in range of commercial products (e.g. [157, 158, 159]) and was chosen as an audio manipulation applicable for both decreasing and increasing awareness of sound events.

Audio Manipulation Implementation Details

The manipulation of the in-VR audio volume was implemented using a linear interpolation method [160]. For the automatic decrease, the volume decreased to 20% of its starting value. For the automatic increase, the volume increased by 66% of its starting value. The initial manipulation of audio, to increase/decrease awareness of the sound event, was performed over a period of half a second. When exposure to the manipulated audio ended (after nine seconds), the volume returned to its starting value using the same linear interpolation method over a one second period.

6.2.2 Study Design

The experiment used a video watching task designed to recreate the affordances and visual/aural demand of home VR entertainment [35, 37, 33, 36]. This provided a usage scenario requiring high levels of attention demand and engagement from the VR user, which would consequentially stress the usability of conditions being evaluated. The video task had participants watch the opening eight minutes of a nature documentary [161] and consisted of a *configuration phase* and an *experimental phase*.

The *configuration phase* was used to set the baseline volume values for the *On-board Audio* and *Headphone Audio* conditions. In this phase, participants were exposed to two forty-five second videos: one to set the baseline volume in the *On-board* conditions and one to set the baseline volume in the *Headphone* conditions. Participants were instructed to set the volume levels as if they were using the VR headset in their home. These baseline values were then used as the starting value from which to increase/decrease the volume in the *Dynamic* variations of the *On-board Audio* and *Headphone Audio* conditions.

The *experimental phase* was then used to evaluate each condition. In this phase, one condition lasted ninety seconds where participants watched a ninety second video and were exposed to the external sound events on a fixed time intervals. The sound events were triggered twenty-five seconds and sixty seconds after the start of the condition. Each sound event played for ten seconds and was produced using a laptop and set of nearby speakers. If applicable, the audio manipulation occurred one second after the sound event started (to simulate the processing times of the headset detecting, recognising and responding to the sound event). The audio manipulations mapped to the sound events as follows:

- ***Door Knock Sound Event:*** automatically decrease the application volume to increase awareness of this sound event
- ***Vacuum Cleaner Sound Event:*** automatically increase the application volume to decrease awareness of this sound event

After each condition ended the participant removed the headset and complete a questionnaire. The condition order was counterbalanced using a four condition balanced Latin square approach. The sound event order was randomised in every condition.

Task Implementation Details

A wizard of approach [162] was used where a timer controlled exposure to the external sound events. When each condition started, a timer controlling the sound events started and triggered them after twenty-five seconds and sixty seconds respectively. The audio manipulations (if applicable) were triggered by the experimenter in response to the external sound events (one second after the sound event audio began). The audio manipulations were not activated instantaneously to replicate the processing delay required for a headset to detect, interpret and respond to a detected sound event. The volume of the external sound events was set to match the decibel levels of an actual door knock (55dB) or vacuum cleaner (75dB) being used in the VR user's nearby area (these were recreated and measured by the experimenter while building the experiment to ensure they were accurate for the room being used).

6.2.3 Questionnaire Measures

A questionnaire was designed to evaluate for each condition: sense of presence in VR and awareness of the external sound events. All questions used a 7-point Likert scale.

- ***Sense of Presence Questions:*** presence was evaluated using the *"Sense of Being There"* and *"Involvement"* subset of the IPQ questionnaire [46] and five Likert scale questions which asked participants to what extent they agreed (1=strongly disagree, 7=strongly agree) they were: (1) *"distracted from VR due to reality"*, (2) *"aware of their surrounding area"*, (3) *"mentally immersed in the experience"*, (4) *"comfortable"* and (5) *"present in the virtual world"*.

- ***Awareness of External Sound Events Questions:*** awareness of the sound events was evaluated using two Likert scale questions which asked to what extent participants were aware (1=extremely unaware, 7=extremely aware): (1) *"of the door knock"* and (2) *"of the vaccum"*.

6.2.4 Apparatus

An Oculus Go headset [156] was used to conduct the experiment. The experimenter used the headset's controller to start each condition and trigger the audio manipulation (when applicable). As such, the participant did not use the controller during the experiment. Participants used the headset's on-board, acoustically transparent [120], audio system of the Oculus Go headset, and a pair of consumer Sony on-the-ear headphones to hear the in-VR audio during the experiment. The external sound events' audio was produced using a pair of consumer speakers attached to a laptop positioned on a table 2.5 metres away from the seated participant. Figure 6.1 shows the experiment setup.

Figure 6.1: The experimental setup used in Experiment 3. The participant sat in the chair using the Oculus Go headset and the experimenter stood to the right of the laptop.

6.2.5 Procedure

Upon arrival the experiment's purpose was explained and a consent form and demographics questionnaire given to the participant. Participants were told the purpose of the experiment was to evaluate the design of audio awareness systems for VR headsets that were designed to direct their attention towards or from sounds in their surrounding real-world environment. Participants were told, whilst watching a documentary in VR, they would hear the sounds of a door knock and vacuum cleaner in their surrounding environment, and that the audio awareness systems being evaluated were designed to increase their awareness of the door knock and decrease their awareness of the vacuum cleaner.

Next, it was explained that the experiment would consist of two parts. First, there would be a configuration phase to capture default volume levels to be used throughout the experiment. After this there would be an experimental phase to evaluate the four conditions being tested. Participants were then instructed where to sit and shown (if required) how to put on and fit the headset. The experimenter then took their position seated 2.5 metres away facing the participant and started the configuration phase. After this was completed the experimental phase began and each condition was evaluated in turn. After all conditions were evaluated, participants were asked to rank order the conditions from best to worse and to discuss how they had ranked their preferences (e.g. prioritising presence, awareness, etc). Participants were also asked if they wished to make any comments about any of the conditions they had experienced.

The experiment took on average twenty-five minutes to complete. Participants participation in the experiment was voluntary.

Awareness of External Sound Events	*(1) On-board Audio*	*(2) Dynamic On-board Audio*	*(3) Headphone Audio*	*(4) Dynamic Headphone Audio*	*Friedman Test*	*Wilcoxon Post-hoc ($p<0.0083$)*
Awareness of Door Knock	4.50 (1.84)	5.75 (1.20)	3.50 (1.90)	6.13 (0.93)	$\chi^2(3) = 16.15$, $p<0.0083$	*3-1, 3-4*
Awareness of Vacuum	6.75 (0.56)	6.93 (0.24)	5.44 (2.24)	6.00 (1.84)	$\chi^2(3) = 8.31$, $p>0.0083$	*N/A*

Table 6.1: Experiment 3's mean (standard deviation) values, and pairwise comparisons, for the awareness of the sound event questions. *Dynamic On-board Audio* and *Dynamic Headphone Audio* both significantly increased *Awareness of Door Knock* from the *Headphone Audio* condition.

6.3 Experiment 3: Results

6.3.1 Participants

Participants were recruited using social media and university mailing lists. 16 participants (7 female, 9 male) completed the experiment. Participants ranged in age from 19 to 31 (M=23.13, SD=3.56). Participants were asked to indicate their prior experience with VR headsets using a 5-point Likert scale (1=none, 5=a lot), (M=2.50, SD=1.32). 10 reported they had at least *"a little (2)"* prior experience with VR.

6.3.2 Analysis

A Friedman test was used to find significant differences between factors and was followed by pairwise comparisons using Wilcoxon signed-rank tests with Bonferroni corrected p-values ($p < 0.0083$). For participants' preference ranking, the average ranking score was calculated for each condition using the rankings given. Participants' qualitative comments were coding using selective coding [121] where participants' statements were assigned emergent codes over repeated cycles with the codes grouped using a thematic approach. A single coder performed the coding and reviewed/discussed the coding with one other researcher. Two coding cycles were performed.

6.3.3 Awareness of External Sound Events Evaluation Results

The mean, standard deviation values and Friedman test results of the sense of presence questions are summarised in Table 6.1. The results of Wilcoxon signed-rank pairwise comparisons are summarised in Table 6.1.

Sense of Presence Factors	*(1) On-board Audio*	*(2) Dynamic On-board Audio*	*(3) Headphone Audio*	*(4) Dynamic Headphone Audio*	***Friedman Test***	***Wilcoxon Post-hoc ($p<0.0083$)***
Distraction	3.88 (1.45)	4.25 (1.25)	3.94 (1.52)	4.19 (1.38)	$\chi^2(3) = 1.33$, $p>0.0083$	N/A
Aware of Surroundings	4.56 (1.37)	4.25 (1.52)	3.69 (1.53)	4.23 (1.52)	$\chi^2(3) = 4.46$, $p>0.0083$	N/A
Mental Immersion	3.69 (1.21)	4.00 (1.50)	4.25 (1.25)	4.00 (1.58)	$\chi^2(3) = 1.83$, $p>0.0083$	N/A
Comfortable	4.88 (1.62)	4.56 (1.22)	4.69 (1.49)	4.44 (1.66)	$\chi^2(3) = 0.77$, $p>0.0083$	N/A
Present in Virtual World	3.81 (1.67)	4.19 (1.51)	4.31 (1.57)	3.94 (1.85)	$\chi^2(3) = 1.26$, $p>0.0083$	N/A
IPQ: Sense of Presence	3.44 (1.46)	3.69 (1.61)	3.88 (1.62)	3.56 (1.84)	$\chi^2(3) = 1.85$, $p>0.0083$	N/A
IPQ: Involvement	3.41 (0.54)	3.42 (0.58)	3.44 (0.74)	3.53 (0.72)	$\chi^2(3) = 0.14$, $p>0.0083$	N/A

Table 6.2: Experiment 3's mean (standard deviation) values, and pairwise comparisons, for the sense of presence questions. With the IPQ questions a higher average score indicates a higher sense of presence in VR. All of the conditions scored comparably across all questions.

Both *Dynamic* conditions (*Dynamic On-board Audio* and *Dynamic Headphone Audio*) were found to be an effective methods of increasing a VR user's awareness of external sound events. Two significant differences were found in the *"Awareness of Door Knock"* question: between *Headphone Audio* and *Dynamic On-board Audio*, and between *Headphone Audio* and *Dynamic Headphone Audio*.

However, both *Dynamic* conditions were found to be ineffective methods of decreasing a VR user's awareness of external sound events. No significant differences were reported as occurring in the *"Awareness of Vacuum"* question. Participants commented during the experiment that this was because the vacuum sound remained loud enough to disrupt their experience despite the increase in volume experienced during the *Dynamic* conditions.

6.3.4 Sense of Presence Evaluation Results

The mean, standard deviation values and Friedman test results of the sense of presence questions are summarised in Table 6.2. The results of Wilcoxon signed-rank pairwise comparisons are summarised in Table 6.2 also.

All of the conditions performed comparably in the sense of presence questions with no significant differences being reported as occurring between any of the conditions. Moderate scores were found across all of the questions. However, that the *Dynamic* conditions did not significantly reduce sense of presence by increasing awareness of the door knock is itself a positive result. This suggests that this audio manipulation (of automatically altering in-VR audio volume) can be introduced to a VR user's experience without significantly disrupting a their sense of presence in VR.

6.3.5 Preference Ranking Results

The average ranking score of participants preference ranking is shown in Table 6.3 where a higher average ranking score indicates a higher preference towards an approach.

Headphone Audio scored highest (2.94 out of 4.00) and was the first choice of 50% of participants. *On-board Audio* scored worst (2.31 out of 4.00) while *Dynamic On-board Audio* and *Dynamic Headphone Audio* both scored 2.38 (although the composition of their scores differs). *Dynamic Headphone Audio* was primarily favoured as the second choice of participants whereas *Dynamic On-board Audio* was primarily favoured as the third choice.

When justifying *Headphone Audio* as their first choice, all 8 participants said they felt the noise cancelling nature of headphones was important for creating a high quality, immersive experience in VR, *P1: "that's just how I like my audio to sound, isolating"*. Additionally, 7 participants indicated they preferred headphones as they did not think the on-board system was of high quality, *P3: "[on-board audio] the quality wasn't that great, the sound was not that immersive"*. Although it should be noted that 4 participants stated if the quality of the on-board system audio was improved they would prefer it to headphones.

Participants who preferred on-board audio (*On-board Audio* and *Dynamic On-board Audio*) indicated that its comfort and convenience made it preferable to headphones. 6 participants expressed a desire to avoid wearing headphones whilst using VR wherever possible stating they did not like the experience this created of being completely unaware of their surrounding environment, *P12: "I don't like not having an awareness of my surroundings, audio is an element of that, it makes me uncomfortable to not have it"*.

Condition / Ranking	*1st*	*2nd*	*3rd*	*4th*	***Average Ranking***
Headphone Audio	8	3	1	4	2.94
Dynamic On-board Audio	3	3	7	3	2.38
Dynamic Headphone Audio	2	6	4	4	2.38
On-board Audio	3	4	4	5	2.31

Table 6.3: The average ranking scores (of a possible 4.0) from the preference ranking of the audio manipulations in Experiment 3. A higher score indicates a higher preference towards an approach. *Headphone Audio* was the preferred approach.

General Comments Regarding In-VR Audio Manipulation

Sentiment towards the *Dynamic* conditions was mixed. 6 participants said they liked the *Dynamic* conditions and said they should be included as an optional feature within VR headsets, *P5: "the option should be there if you want it, I think some people definitely would use it"*. However, 7 participants believed the on-board, acoustically transparent, audio systems of VR headsets would be sufficient whenever increased aural awareness was desired and so additional awareness systems are unnecessary, *P2: "If I want awareness open ear is enough"*. However, Chapter 4 of this thesis demonstrates that suggestion is inaccurate as it collected evidence of both failed verbal bystander-VR user interactions with VR users and evidence of some user's exiting VR either partially or fully to accommodate an interaction with a bystander. Note: this finding is further reinforced by the results of Experiment 4 within this chapter (Section 6.6). Finally, 3 participants believed there would be too much variability regarding whether they wanted to hear an external sound and for how long they would want to hear it, and so would prefer to manage the in-VR audio volume manually as appropriate, *P11: "I would rather decide and change the volume myself because sometimes things I don't want to hear could change into something I do want to hear"*.

6.4 Experiment 3: Discussion

6.4.1 Automatic Decreases of in-VR Audio Volume Were Effective at Increasing Awareness of External Sound Events

Experiment 3's results show that an automatic decrease of in-VR audio volume can be used to effectively increase a VR user's awareness of nearby sound events. This is a positive result and suggests automatic volume adjustments are a promising approach for increasing a VR user's awareness of nearby sound events (e.g. a door knock) and for facilitating a verbal bystander-VR user interaction. Furthermore, all of the evaluated conditions were found to be comparable in terms of the VR user's sense of presence. This too is a positive result as it suggests an increase in aural awareness can be achieved without significantly disrupting a VR user's sense of presence or enjoyment in VR. This result is in-line with the findings of prior work which have demonstrated in-VR audio can be manipulated without significantly disrupting enjoyment or sense of presence [66, 60, 69].

However, Experiment 3's results are limited with respect to their investigation of the impact of these audio manipulations on a VR user's sense of presence due to the limited exposure times used within the experiment. As the aim of this experiment was primarily to investigate the effectiveness of, and general attitudes towards, automatic volume adjustments for increasing/decreasing a VR user's reality awareness, the approach used in the experiment was considered sufficient for this purpose. Future work, that is beyond the scope of this thesis, could perform a comprehensive investigation of the impact on sense of presence of in-VR audio manipulations across a wide variety of parameters (e.g. application types, audio manipulation technique, exposure to various sound events, etc). In particular inspiration could be taken from Luca et al's *"Locomotion Vault"* [163] which shows how a breadth of research solutions can be evaluated, based on standardised measures, allowing contributions to be better placed in context against prior work. Constructing such a comprehensive, single resource for the influence of different audio manipulations on a VR user's sense of presence would provide designers with a resource to find appropriate solutions to problems they face and identify gaps for future designs.

6.4.2 Attitudes Towards In-VR Audio Manipulation

Although sentiment towards the *Dynamic* conditions was mixed it should be noted that the justification given by participants who preferred *Headphone Audio* was they were attempting to maximise immersion in VR. This, is a type of VR user preference towards how their awareness of reality should be managed whilst in VR [72, 37]. For example, for individuals who aim to maximise immersion in VR, this is an attempt to prioritise immersion by minimising external disruptions where possible. The *Dynamic* conditions in Experiment 3, philosophically, go against this preference by attempting to contextually increase the VR user's awareness of reality. Therefore it is not surprising that some VR users might prefer the *Headphone Audio* over the *Dynamic* conditions. However, as highlighted by Experiment 2 (Section 4), VR users differ in their awareness needs and preferences. So while some VR users will attempt to prioritise immersion, others will to opt balance their awareness of reality with immersion in VR, or even prioritise their awareness of reality.

Furthermore, prior work has shown the context in which a bystander awareness system is evaluated can influence attitudes towards it [56]. In Experiment 3, participants were exposed to general sound events (e.g. a door knock / vacuum cleaner). However, exposure to a verbal bystander-VR user interaction may elicit a different response (e.g. a more positive one given the obvious importance of aural awareness during a verbal exchange). Therefore, while Experiment 3 provides insights into the effectiveness of automatically decreasing in-VR audio volume to increase awareness of nearby sound events, further work is needed that evaluates this approach in the context of verbal bystander-VR user interactions. For this reason Experiment 4 was designed to evaluate automatic in-VR audio volume manipulation, and additional audio manipulation approaches, to facilitate a verbal bystander-VR user interaction.

6.5 Experiment 4: Design

The results of Experiment 3 showed automatically decreasing in-VR audio volume could be used to increase a VR user's awareness of a nearby sound event. Furthermore, as highlighted in the literature review of this thesis (particularly Section 2.4), recent works have shown that a VR user's experienced in-VR audio can be manipulated (e.g. by removing audio elements such as background music or sound effects) without influencing the user's sense of presence in VR [66, 155, 69]. Therefore, an experiment was conducted to investigate the effectiveness of facilitating a verbal bystander-VR user interaction by manipulating in-VR audio using four approaches: (1) automatically lowering volume, (2) removing background audio, (3) removing sound effect audio, and (4) removing all audio. The experiment used a game task where participants played an arcade-style VR game and engaged in a verbal interaction with the experimenter. For each audio manipulation, its effectiveness of facilitating a verbal bystander-VR user interaction, the VR user's sense of presence, and its usability was evaluated. Participants' preference towards the four developed audio manipulations was also captured.

6.5.1 Experimental Task

The experiment used a game task that was designed to recreate the affordances and visual/aural demand of home VR entertainment applications [35, 37, 36, 33]. An arcade-style game was developed which tasked participants with throwing cubes at moving targets to score points (similar to [20]). The game was designed to be a fixed, standing experience where users predominantly looked straight ahead and occasionally to their right. This ensured, by design, participants faced the experimenter who sat opposite them four metres away, and is an approach used in prior works to control the positioning of the participant during an experiment (e.g. [21, 20, 6, 22, 56, 10]).

The Game's Gameplay Design

The game was designed to be a visually and aurally demanding experience for users that required continuous player movement and direct interaction with the virtual environment. Such an experience is representative of current, consumer VR applications [36, 37] and is ecologically valid given the reliance on direct user interactions in existing VR games [33, 35].

The game's task was to throw cubes at moving targets to score points within a fixed time period. This was chosen as a simple, yet effective, way of creating engaging gameplay [54].

One point was gained for every target destroyed and two points lost if a target self-destructed (if it was not destroyed quickly enough after spawning). The targets' spawn area was fixed to focus the user's attention forwards (in the direction of the experimenter). To add challenge to the gameplay, a target's design varied by shape (either a cube or cuboid) and movement (either stationary, moving left-to-right in front of the participant or away-and-toward the participant). These parameters were randomly selected every time a new target spawned from a range decided during playtesting of the application by the experimenter.

The Game's Audio Design

The game audio consisted of two elements: *background* and *sound effect* audio. The background audio was persistent, non-diegetic audio present while the game was being played - an upbeat instrumental track. The sound effect audio was a one-off, diegetic sound effect emitted when a target was destroyed - a *"pew"* sound if destroyed by the participant and an electric static *"pist"* sound if it self-destructed.

During development a small pilot test was conducted where five individuals were shown the game and asked: if the audio matched the game's aesthetic, and if they could clearly hear the sound effects over the background audio (e.g. could they determine when a target was destroyed without looking). This was to ensure the audio fit thematically with game's aesthetic (as mismatches can influence player experience [164]) and that the sound effects were noticeable (as one condition involved their removal). All agreed the audio fit thematically and their feedback was used to balance the background and sound effect audio.

6.5.2 Design of the Audio Manipulations

The design of the four in-VR audio manipulations was derived from the findings of prior works and the results of Experiment 3. The four audio manipulations were:

- ***Dynamic Audio:*** Automatically decrease the VR application's volume (to 25% of its starting volume), motivated by the results of Experiment 3 (Section 6.3).
- ***Remove Sound Effect Audio:*** Remove sound effect audio, background audio remains at full volume, motivated by [66, 60, 69, 57]
- ***Remove Background Audio:*** Remove background audio, sound effect audio remains at full volume, motivated by [66, 60, 69, 57]

- ***Remove All Audio:*** Remove background and sound effect audio (all audio), motivated by the results of Survey 2 (Section 4.3) and [155, 1]

Dynamic Audio was included as Experiment 3 (Section 6.3) indicated it could be used to effectively increase a VR user's awareness of nearby sounds. Removing partial audio (*Remove Sound Effect Audio* and *Remove Background Audio*) was included to investigate how the phenomena of removing in-VR audio elements without altering a VR user's sense of presence (e.g. [66, 60, 69]) might be used to facilitate verbal interactions. Finally, *Removing All Audio* was included to investigate the extreme of fully removing aural presence (the aural equivalent of removing the headset) as the results of Survey 2 (Section 4.3) found some VR users do this (by removing headphones or muting the volume) during bystander-VR user interactions. A demonstration of the audio manipulations and game task is provided here[1]

Audio Manipulations Implementation Details

The audio manipulations were designed be triggered upon detection of external speech. As in Experiment 3, and prior works in the literature [24, 20, 22], a wizard of oz approach [162] was used to conduct the experiment. In Experiment 4, the manipulation of the in-VR audio was operated on a timer (outlined in detail in Section 6.5.3) and the bystander's verbal interaction timed to start one second before the audio manipulation was triggered.

As instant transitions between virtuality and reality can be jarring and disruptive for users [94, 55], a fading effect was used to add/remove the audio manipulation. All approaches used used the same linear interpolation method [160] as Experiment 3 (outlined in detail in Section 6.2.1), to decrease/remove the audio over half a second. The same effect was also used to increase/return the audio to its starting state when exposure to the manipulated audio ended over a period of one second.

6.5.3 Study Design

The experiment had five conditions: one for each of the four audio manipulations and a baseline (no audio manipulation) condition. The experiment contained two parts: a *training phase* and an *experimental phase*.

The *training phase* was used to introduce each condition to the participant to ensure they were familiar with all of the approaches before they evaluated any one of them. In this phase,

[1] `https://www.youtube.com/watch?v=YtxuimMgPC4`

one condition (one session of the game) lasted fifty seconds with thirty seconds exposure to the audio manipulation (starting after fifteen seconds). Before starting each condition, the experimenter introduced the condition to the participant (e.g. *"This is the remove all audio condition, all of the audio will be removed, ok start when you are ready"*).

The *experimental phase* was used to evaluate each condition. In this phase, one condition lasted ninety-five seconds with sixty seconds exposure to the audio manipulation (starting after twenty-five seconds). Here, when the condition started, the experimenter began a timer and after twenty-four seconds, just before the audio manipulation triggered, initiated a verbal interaction with the bystander using prepared conversation starters. After each condition ended the participant removed the headset and completed a questionnaire. The condition order was counterbalanced using a five condition balanced Latin square approach.

Conversation Starters

In the experimental phase, prepared conversation starters were used to initiate a verbal interaction between the bystander (the experimenter) and the VR user (the participant). These were structured so the experimenter made a statement, asked a question then asked follow up questions based on the participant's responses. The experimenter ended the conversation as exposure to audio manipulation ended. The five conversation starters were:

- *"I'm thinking of having pizza for dinner later, do you know what you are going to eat for dinner today?"*
- *"I've been listening to a lot of The Beatles lately, have you been listening to anything in particular lately?"*
- *"I've always wanted to go to Egypt to see the pyramids, is there anywhere in the world that you want to see?"*
- *"My full time job is to conduct research into human-computer interaction, what do you do?"*
- *"My favourite colour is purple, what's your favourite colour and why?"*

The experimenter used a decibel meter to monitor the volume of their speaking voice during the experimental phase and first spoke at approximately 60dB (the average human speaking volume [165]). If the participant failed to hear this, the experimenter repeated themselves at approximately 75dB. If the participant again failed to hear, the experimenter tried again at 75dB before giving up. The experimenter noted when a participant failed to hear any attempt to initiate a verbal interaction and any other relevant observations or comments made (e.g. the participant saying *"I can't really hear you"* in response to the experimenter speaking). Prior to conducting the experiment, the experimenter rehearsed their timing and speaking volume fifteen times. The conversation starter order was counterbalanced using a five condition balanced Latin square approach.

6.5.4 Questionnaire Measures

A questionnaire was designed to evaluate each condition's: effectiveness to facilitate a verbal bystander-VR user interaction, sense of presence, and the usability of the audio manipulations. All questions used a 7-point Likert scale. The usability questions were not asked for the baseline condition as the questions were not applicable.

- ***Facilitating Verbal Interactions Questions:*** measured effectiveness of the condition to facilitate a verbal interaction using six questions which asked to what extent participants agreed (1=strongly disagree, 7=strongly agree): (1) *"It felt as if you and the person you heard were together in the same place"*, (2) *"I could successfully converse with the experimenter"*, (3) *"I could clearly hear the experimenter"*, (4) *"Talking, whilst wearing the headset, felt uncomfortable"*, (5) *"The experimenter was easy to understand"*, and (6) *"The conversation felt natural"*.
- ***Sense of Presence Questions:*** presence was evaluated using: (1) the *"Sense of Being There"* subset of the IPQ questionnaire [46], and two questions derived from similar questions asked in prior works [6, 9, 20, 166] which asked to what extent participants agreed (1=strongly disagree, 7=strongly agree): (2) *"I enjoyed my experience in VR"*, and (3) *"I was too aware of my real world surroundings"*.
- ***Usability Questions:*** usability was evaluated using seven questions which asked to what extent participants agreed (1=strongly disagree, 7=strongly agree) the audio manipulation: (1) *"was disruptive"*, (2) *"was frustrating"*, (3) *"was urgent"*, (4) *"felt natural"*, (5) *"was easy to understand"*, (6) *"was informative"*, and (7) *"improved their ability to verbally interact with a bystander"*.

6.5.5 Apparatus

A Meta Quest 2 headset [32] was used to conduct the experiment. The Quest 2's on-board, acoustically transparent [120], audio system was used in all of the conditions. Figure 6.2 shows the experimental setup.

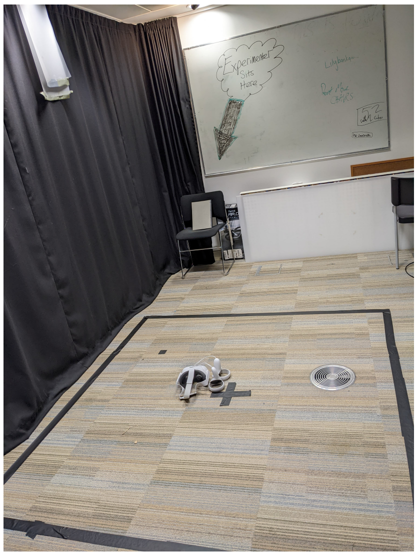


Figure 6.2: The experimental setup used in Experiment 4. The participant stood on the cross facing the experimenter who sat in the chair facing the participant. The black rectangle on the floor outlines the approximate play area of the VR user.

6.5.6 Procedure

Upon arrival the experiment's purpose was explained and a consent form and demographic questionnaire was given to the participant. Participants were told they would be playing a VR game and would experience four aural awareness systems designed to improve their ability to engage in a verbal interaction with a non-VR bystander. It was explained that the experiment would consist of two parts: a first part to introduce each awareness system to them then a second part to evaluate each approach. Participants were told during the second part that the experimenter would act as a known bystander (e.g. a friend they lived with) and verbally interact with them, that they were free to respond as they wished, and it was fine if they did not hear the experimenter. A demonstration video of the game was then shown and its controls explained. Participants were then instructed where to stand during the experiment and shown (if required) how to put on and fit the headset. The experimenter then took their position seated four metres away, facing the participant, on the opposite side of the room.

Participants then began the training phase. During this phase, participants were told to set the system volume of the headset to a *"comfortable but immersive"* level. Most set it to about 60% system volume, a level which meant the experimenter could also clearly hear the audio being emit from the headset. After the training phase was completed participants were instructed to take off the headset and were given the opportunity to take a break while the experimenter set up the experimental phase. Once ready, the participant and experimenter returned to their positions and began the experimental phase where each condition was evaluated in turn. After all conditions were evaluated, participants were asked to rank order the four awareness systems from best to worse and to justify how they had ranked their preferences (e.g. prioritising presence, awareness, etc). Finally, participants were asked if they had any comments regarding any of the systems they had experienced.

The experiment took on average twenty-five minutes to complete. Participants were paid a £5 Amazon voucher for participating.

6.6 Experiment 4: Results

6.6.1 Participants

Participants were recruited using social media and university mailing lists. 15 participants (7 female, 8 male) completed the experiment. Participants ranged in age from 19 to 40 (M=24.80, SD=5.48). Participants were asked to indicate their prior experience with VR using a 5-point Likert scale (1=none, 5=a lot), (M=3.73, SD=1.22). All reported having at least *"a little (2)"* prior experience with VR. As the task involved a verbal interaction, participants were asked if they were a native English speaker (10 yes, 5 no) and to rate their English proficiency using a 5-point Likert scale (1=basic, 5=native), (M=4.67, SD=0.49).

6.6.2 Analysis

A Friedman test was used to find significant differences between factors and was followed by pairwise comparisons using Wilcoxon signed-rank tests with Bonferroni corrected p-values. For participants' preference ranking, the average ranking score was calculated for each condition using the rankings given. Participants' comments, used to justify their ranking, were coding using selective coding [121] where participants' statements were assigned emergent codes over repeated cycles with the codes grouped using a thematic approach. A single coder performed the coding and reviewed/discussed the coding with one other researcher. Analysis of the observations followed a similar approach where the experimenter's notes were coded then reviewed/discussed with one other researcher. Two coding cycles were performed.

6.6.3 Observations Made During Verbal Interaction

Observations made during the experiment are summarised in Table 6.4.

Baseline and *Remove Sound Effect* were the most problematic conditions. Both had 1 participant fail to hear all attempted verbal interactions and multiple participants requiring the experimenter speak louder to be heard. This is somewhat expected as these conditions provide the lowest amounts of external aural awareness to a VR user, and is in-line with prior findings of this thesis (Experiment 1 and Survey 2) that acoustically transparent, on-board audio systems can be ineffective at facilitating verbal bystander-VR user interactions. Additionally, the similarity experiencing the *Baseline* and *Remove Sound Effect* conditions was commented on by 5 participants who said (regarding the *Remove Sound Effect* condition) they *P10: "didn't notice what it did to the audio at all"*.

Issues, however, were not exclusive to these conditions as 2 participants also required the experimenter speak louder during the *Dynamic Audio* condition.

6.6.4 Facilitating the Verbal Interaction Evaluation Results

The mean, standard deviation values and Friedman test results of the facilitating the verbal interaction questions are summarised in Table 6.5. The results of Wilcoxon signed-rank pairwise comparisons are summarised in Table 6.5 also.

The *Dynamic Audio*, *Remove Background*, and *Remove All Audio* conditions all significantly improved the VR user's ability to engage in a verbal interaction and so effectively facilitated the verbal interaction. The *Remove Sound Effects* condition made minimal impact and was instead comparable with the *Baseline*, both of which were found to be ineffective at facilitating the verbal interaction (Table 6.5).

Significant differences were found in all of the *"facilitating verbal interactions"* questions (Table 6.5). The same six significant difference pairings were found across questions: *(1)*

Observation	***Count***
— Baseline (No Manipulation)	
Missed attempted interaction	1
Repeated self louder to be heard	5
— Remove Sound Effects	
Missed attempted interaction	1
Repeated self louder to be heard	4
— Dynamic Audio	
Repeated self louder to be heard	2

Table 6.4: Observations made during the experimental phase of Experiment 4

felt together in the same place, *(2) could successfully converse*, *(3) could clearly hear*, *(5) experimenter was easy to understand*, and *(6) conversation felt natural*. These were three significant differences between the *Baseline* and the *Dynamic Audio*, *Remove Background* and *Remove All Audio* conditions, and three significant differences between the *Remove Sound Effects* and the *Dynamic Audio*, *Remove Background* and *Remove All Audio* conditions. This suggests the *Baseline* and *Remove Sound Effects* conditions are comparable and that the removal of sound effects, in this experiment, made no difference to participants' experienced verbal interaction.

This result is also reflected in the mean scores (Table 6.5) where the *Baseline* performed worst, *Remove Sound Effects* only marginally better, and *Dynamic Audio*, *Remove Background* and *Remove All Audio* all significantly better. While somewhat expected, one would expect as more audio is removed/reduced that the VR user would be able to hear more of their surrounding environment, the results do show partial removal of audio (e.g. *Remove Background*) or volume decreases (e.g. *Dynamic Audio*) can facilitate verbal interactions with comparable effectiveness as removing all audio (e.g. *Remove All Audio*).

Finally, regarding: *(4) talking, wearing the headset, was uncomfortable*, while the *Baseline* performed worst (M=4.47) its mean score still indicated that participants found it *"it neither uncomfortable nor comfortable"*. All other conditions scored lower indicating participants were comfortable with all of the audio manipulations, although, only one significant difference was found between the *Baseline* and *Remove Background* conditions. However, the difference between these conditions does highlight the positive benefit bystander awareness

Facilitating Interaction	*(1) Baseline*	*(2) Dynamic Audio*	*(3) Remove Background*	*(4) Remove Sound Effects*	*(5) Remove All Audio*	***Friedman Test***	***Wilcoxon Post-hoc (p<0.005)***
Felt together in same place	3.60 (1.58)	5.40 (1.20)	5.93 (0.68)	3.93 (1.91)	5.80 (0.91)	$\chi^2(4) = 25.65$, $p < 0.005$	1-2, 1-3, 1-5, 2-4, 3-4, 4-5
Could successfully converse	2.13 (1.02)	5.60 (1.50)	6.33 (0.70)	3.33 (1.62)	6.27 (1.12)	$\chi^2(4) = 41.97$, $p < 0.005$	1-2, 1-3, 1-5, 2-4, 3-4, 4-5
Could clearly hear the experimenter	1.67 (0.70)	5.60 (1.62)	6.27 (0.85)	2.80 (1.64)	6.67 (0.60)	$\chi^2(4) = 42.87$, $p < 0.005$	1-2, 1-3, 1-5, 2-4, 3-4, 4-5
Talking, wear the headset, was uncomfortable	4.47 (1.59)	3.47 (1.82)	2.40 (1.25)	3.73 (1.91)	2.80 (1.68)	$\chi^2(4) = 17.13$, $p < 0.005$	1-3
Experimenter was easy to understand	2.00 (0.73)	5.53 (1.59)	6.27 (0.85)	3.33 (1.70)	6.53 (0.72)	$\chi^2(4) = 43.19$, $p < 0.005$	1-2, 1-3, 1-5, 2-4, 3-4, 4-5
Conversation felt natural	3.40 (1.50)	5.27 (1.29)	5.87 (0.88)	3.67 (1.81)	5.40 (1.25)	$\chi^2(4) = 33.33$, $p < 0.005$	1-2, 1-3, 1-5, 2-4, 3-4, 4-5

Table 6.5: Experiment 4's mean (standard deviation) values, and pairwise comparisons, for the facilitating interaction questions. *Remove Background* and *Remove All Audio* increased awareness most. *Remove Sound Effects* performed poorly and was comparable to *Baseline*.

systems can have on some VR users' comfort. For the *Baseline*, 53.33% of participants agreed (13.33% weakly agree, 40% agree) they were uncomfortable engaging in the verbal interaction whilst wearing the headset. However, for *Remove Background*, this reduced to only 6.67% of participants stating they were uncomfortable, highlighting how a noticeable increase in comfort can be made by audio manipulations, and bystander awareness systems more generally, and the increased awareness provided.

6.6.5 Sense of Presence Evaluation Results

The mean, standard deviation values and Friedman test results of the sense of presence questions are summarised in Table 6.6. The results of Wilcoxon signed-rank pairwise comparisons are summarised in Table 6.6 also.

The *Dynamic Audio, Remove Background,* and *Remove All Audio* conditions all significantly decreased the VR user's sense of presence. *Remove Sound Effects* did not and was comparable to the *Baseline* (Table 6.6).

For *IPQ: Sense of Presence* five significant differences were found: three between the *Baseline* and *Dynamic Audio*, *Remove Background* and *Remove All* conditions, and two between *Remove Sound Effects* and the *Dynamic Audio* and *Remove All Audio* conditions (Table 6.6). No significant difference were found between the *Baseline* and *Remove Sound Effects* reinforcing their similarity. The more substantial audio manipulations (e.g. *Dynamic Audio*, *Remove Background*, *Remove All Audio*) caused a higher decrease in presence, although, *Dynamic Audio* (M=4.11) retained more presence than both *Remove Background* (M=3.55) and *Remove All Audio* (M=3.60).

Despite this decrease in presence, participants enjoyment varied minimally across the conditions (mean scores ranging from 5.20 to 5.60) and no significant differences were reported as occurring between the conditions in this respect. Furthermore, participants did not consider any condition to make them *"too aware"* of their surrounding reality (Table 6.6). Therefore, despite mean scores increasing as more substantial audio manipulations were made, no condition was said to increase awareness too much.

6.6.6 Usability Evaluation Results

The mean, standard deviation values and Friedman test results of the usability questions are summarised in Table 6.7. The results of Wilcoxon signed-rank pairwise comparisons are summarised in Table 6.7 also. Each usability question is discussed, in turn, below.

Sense of Presence	*(1) Baseline*	*(2) Dynamic Audio*	*(3) Remove Background*	*(4) Remove Sound Effects*	*(5) Remove All Audio*	*Friedman Test*	*Wilcoxon Post-hoc (p<0.005)*
IPQ: Sense of Presence	5.15 (0.98)	4.11 (0.83)	3.55 (0.91)	4.87 (0.97)	3.60 (1.07)	$\chi^2(4) = 19.45$, $p < 0.005$	1-2, 1-3, 1-5, 2-4, 4-5
Enjoyed the VR experience	5.33 (1.58)	5.60 (1.53)	5.33 (1.53)	5.60 (1.45)	5.20 (1.68)	$\chi^2(4) = 2.33$, $p > 0.005$	N/A
Was too aware of my real world surroundings	1.93 (1.24)	2.40 (1.58)	3.13 (1.71)	1.80 (0.65)	3.40 (1.85)	$\chi^2(4) = 11.47$, $p > 0.005$	N/A

Table 6.6: Experiment 4's mean (standard deviation) values, and pairwise comparisons, for the sense of presence questions. For the IPQ questions a higher value indicates a greater sense of presence in VR. More substantial audio manipulations decreased presence but did not alter enjoyment of the experience.

Usability	*(1) Dynamic Audio*	*(2) Remove Background*	*(3) Remove Sound Effects*	*(4) Remove All Audio*	*Friedman Test*	*Wilcoxon Post-hoc (p<0.0083)*
Was disruptive	2.67 (1.35)	3.53 (1.50)	1.93 (1.29)	4.27 (1.69)	$\chi^2(3) = 14.28$, $p < 0.0083$	1-4, 2-3, 3-4
Was frustrating	2.40 (1.45)	2.20 (1.11)	2.80 (2.01)	3.07 (1.53)	$\chi^2(3) = 2.16$ $p > 0.0083$	N/A
Was urgent	2.13 (0.81)	3.67 (1.62)	1.60 (1.02)	4.67 (1.78)	$\chi^2(3) = 22.26$ $p < 0.0083$	1-4, 2-3, 3-4
Felt natural	4.93 (1.48)	5.80 (0.91)	3.20 (2.14)	5.00 (1.15)	$\chi^2(3) = 14.10$ $p < 0.0083$	2-3, 3-4
Was easy to understand	5.73 (0.93)	5.80 (0.91)	2.33 (1.53)	6.27 (0.93)	$\chi^2(3) = 26.74$ $p < 0.0083$	1-3, 2-3, 3-4
Was informative	4.67 (1.45)	4.93 (1.84)	1.80 (1.33)	5.53 (1.20)	$\chi^2(3) = 21.94$ $p < 0.0083$	1-3, 2-3, 3-4
Improved ability to verbally interact	6.07 (0.93)	6.60 (0.61)	2.27 (1.48)	6.40 (0.71)	$\chi^2(3) = 28.82$ $p < 0.0083$	1-3, 2-3, 3-4

Table 6.7: Experiment 4's mean (standard deviation) values, and pairwise comparisons, for the usability questions. *Dynamic Audio*, *Remove Background* and *Remove All Audio* performed well, albeit somewhat more disruptive than *Remove Sound Effects*, although this did not cause a rise in frustration.

Disruptive

The more substantial audio manipulations (e.g. *Remove Background* and *Remove All Audio*) caused higher levels of disruption to participant's experience in VR, although *Remove All Audio* was the only condition considered disruptive. Three significant differences were found: between *Remove All Audio* and the *Dynamic Audio* and *Remove Sound Effects* conditions and between *Remove Background* and *Remove Sound Effects*. Noteworthy, is *Dynamic Audio* which, similar to its performance in the sense of presence evaluation, was not considered as disruptive to the experience as the *Remove Background* and *Remove All Audio* conditions.

Frustrating

No condition was considered frustrating which is a positive result for all of the conditions. No significant differences were found between the conditions. Similar to disruption, *Remove All Audio* scored highest although it was still not considered frustrating by participants.

Urgency

The more substantial audio manipulations (e.g. *Remove Background* and *Remove All Audio*) were considered to be more urgent than the other conditions. Three significant differences were found: between *Remove All Audio* and the *Dynamic Audio* and *Remove Sound Effects* conditions and between *Remove Background* and *Remove Sound Effects*. As with disruption, no significant difference was found between *Dynamic Audio* and *Remove Sound Effect* reinforcing that *Dynamic Audio* was considered by the participants to be less intrusive than *Remove Background* and *Remove All Audio*.

Natural

Dynamic Audio, *Remove Background*, and *Remove All Audio* were said to be natural ways increasing awareness. *Remove Sound Effects* was not, likely because participants regarded it as insufficient for increasing awareness. *Remove Background* was considered the most natural condition with comments made by 3 participants providing some insight into why when they described it as *P15: "the most obvious attempt at reducing audio but maintaining presence"*. These participants felt increased awareness should be balanced with retained immersion in VR and believed that *Remove Background* most obviously attempted to achieve this. Two significant differences were found: between *Remove Sound Effects* and the *Remove Background* and *Remove All Audio* conditions.

Easy to Understand

Dynamic Audio, *Remove Background* and *Remove All Audio* were well understood by participants. *Remove Sound Effects* was not, likely because it frequently went unnoticed. During the experiment 5 participants commented on this directly by stating they *P11: "didn't notice"* how it differed from the *Baseline* condition. Three significant differences were found: between *Remove Sound Effect* and all of the other conditions.

Informative

Dynamic Audio, *Remove Background* and *Remove All Audio* were considered informative while *Remove Sound Effects* was not. Again this is likely attributed to participants view of *Remove Sound Effects* being comparable to the *Baseline* condition. Three significant differences were found: between *Remove Sound Effect* and all of the other conditions.

Improved Ability To Verbally Interact

Dynamic Audio, *Remove Background* and *Remove All Audio* were said to improve participants' ability to engage in a verbal interaction. All three performed comparably and the results are similar to those seen in the questions investigating their effectiveness at facilitating verbal interactions (Section 6.6.4). As in those results, in this experiment, *Remove Sound Effects* was not considered sufficient for facilitating a verbal interaction while the other conditions were. Three significant differences were found: between *Remove Sound Effects* and all of the other conditions.

6.6.7 Preference Ranking Results

The average ranking score of participants preference ranking is shown in Table 6.8 where a higher average ranking score indicates a higher preference towards an approach.

Dynamic Audio scored highest (3.27 out of 4.00) and was the first choice of 60% of participants. *Remove Sound Effects* performed worst (1.13 out of 4.00) which is expected given its

Condition / Ranking	*1st*	*2nd*	*3rd*	*4th*	***Average Ranking***
Dynamic Audio	9	2	3	1	3.27
Remove All Audio	4	5	5	1	2.80
Remove Background	2	8	5	0	2.80
Remove Sound Effects	0	0	2	13	1.13

Table 6.8: The average ranking scores (of a possible 4.00) from the preference ranking of the audio manipulations in Experiment 4. A higher score indicates a higher preference towards an approach.

performance across the other evaluation metrics. *Remove Background* and *Remove All Audio* both scored 2.80 although the composition of their scores differs. *Remove Background* was favoured primarily as a second choice of participants whereas *Remove All Audio* was spread more uniformly across the first, second and third choice of participants.

When justifying their ranking, 11 participants said they preferred increased awareness be balanced with maintaining presence in VR. 9 of this 11 selected *Dynamic Audio* as their first choice as they viewed it *P1: "the best compromise of awareness and immersion"*. The other 2 selected *Remove Background* as their first choice as they were *P12: "slightly in favour of prioritising awareness"*. The remaining 4 participants all ranked *Remove All Audio* as their first choice and indicated their only concern and priority was increasing their awareness regardless of the cost to their sense of presence in VR, *P10: "I want awareness and don't care what my immersion is like at that point"*.

6.7 Experiment 4: Discussion

6.7.1 Effective In-VR Audio Manipulations to Facilitate Verbal Bystander-VR User Interactions

The results of Experiment 4 show that *Dynamic Audio, Remove Background* and *Remove All Audio* all significantly improved participants ability, as a VR user, to engage in a verbal interaction with a bystander. As such, all three were found to be effective methods of manipulating in-VR audio to facilitate a verbal bystander-VR user interaction. However, this aural awareness was found to reduce a VR user's sense of presence, highlighting the potential trade off between enabling interactions and disrupting presence in VR. Although, it should be noted, this decreased presence was not said to alter participants' enjoyment of their experience in VR, nor did participants believe it made them *"too aware"* of their surrounding reality. This is positive result then, as the results of Experiment 4 identify three effective methods of manipulating in-VR audio to facilitate a verbal bystander-VR user interaction that retain the user's enjoyment of their VR experience (albeit with varying amounts of disruption to the user's sense of presence).

6.7.2 Ineffective Methods of Facilitating Verbal Bystander-VR User Interactions

Not all of the evaluated conditions in Experiment 4 were found to be effective methods of facilitating verbal bystander-VR user interactions. *Remove Sound Effects* did not improve participants ability to engage in a verbal interaction and instead was found to be comparable to the *Baseline* condition (which was also found to be ineffective) throughout Experiment 4. This, albeit inconspicuously, is also a positive result though as it: (a) reaffirms the findings of prior works [66, 155, 60, 69] that in-VR audio elements can be removed without impacting the user's sense of presence, and (b) in the context of this thesis, provides further evidence of the shortcomings of the on-board, acoustically transparent, audio systems of VR headsets that further justify the need to develop awareness systems to increase a VR user's aural awareness of their surrounding environment.

Observations made during Experiment 4 (Section 6.4) highlight such shortcomings of the on-board, acoustically transparent, audio systems of VR headsets. During the *Baseline* condition (the default on-board, acoustically transparent, audio system of the Quest 2 headset) a third of the participants required the experimenter speak louder to be heard and one participant missed all attempts at initiating the verbal interaction. Similar observations were made for the *Remove Sound Effects* condition where four participants required the experimenter speak louder to be heard and one participant missed all attempts at initiating the verbal interaction. Furthermore, *Remove Sound Effects* performed comparable to the *Baseline* in all of the other evaluation factors: in its effectiveness at facilitating a verbal interaction (Section 6.6.4), its impact of sense of presence (Section 6.6.5), and its usability (Section 6.6.6).

These results reinforce the findings of Chapter 4 which reported occurrences of similar failed verbal bystander-VR user interactions in-the-wild, and that some VR users partially/fully remove in-VR audio to facilitate a verbal interaction with a bystander. While some participants during Experiment 3 speculated the on-board, acoustically transparent, audio system present in VR headsets would provide sufficient aural awareness of their surrounding environment (Section 6.3), the results of Chapter 4 and Experiment 4 demonstrate this is not the case. Instead, the existing solution present in VR headsets was repeatedly found to be inadequate for providing the VR user with sufficient levels of aural awareness to engage in a (prolonged) verbal bystander-VR user interaction. While such systems may be sufficient for attracting a VR user's attention verbally (e.g. the successful verbal interruptions seen in Experiment 1 (Section 3.6)) these results suggest that such systems are insufficient for prolonged verbal exchanges between a bystander and VR user.

Consequentially, if VR users are to remain in VR but engage in a prolonged verbal interaction with a bystander then awareness systems are needed with the specific purpose of increasing a VR user's aural awareness to support these interactions. To this end, Experiment 3 demonstrates that automatically decreasing in-VR audio volume can be used to effectively increase awareness of nearby sound events of interest, while Experiment 4 identifies *Dynamic Audio, Remove Background* and *Remove All Audio* as three effective methods of manipulating in-VR audio to facilitate a verbal bystander-VR user interaction.

6.7.3 VR User's Aural Awareness Preference & Sense of Presence in VR

Eleven participants in Experiment 4 indicated they preferred increased awareness be balanced with retained presence/immersion in VR. The majority of these participants felt *Dynamic Audio* best fit this aim. The results of usability evaluation reinforce this, as *Dynamic Audio* performed comparable to *Remove Background* and *Remove All Audio* at facilitating a verbal interaction while being less disruptive to the user's experience in VR. However, four participants held a different view of how their aural awareness should be increased and said they were uninterested in balancing awareness with retained presence/immersion. Instead, these four participants indicated they preferred to fully prioritise increasing awareness no matter the cost to their sense of presence in VR (e.g. *Remove All Audio*).

That participants attitudes towards increasing their awareness would differ like this is not unexpected, however, as the results of Experiment 2 also reported VR users with differing attitudes towards how bystander awareness should be increased (e.g. some users are comfortable being notified of bystander existence without positional information while others are not). Significant also is the finding (also found in Experiment 2) that VR users do not select awareness preferences based solely on retained sense of presence. In Experiment 4, four participants indicated they wanted to fully prioritise their aural awareness no matter the impact to their experienced sense of presence. For these individuals, the additional presence retained from another approach (e.g *Dynamic Audio*) did not justify the decreased aural awareness levels and the subsequent increased anxiety/frustration this would cause them (which would further hinder their enjoyment/productivity with any application in use).

This suggests that a range of awareness systems each providing varying levels of awareness/presence need be available to the VR user. At a minimum the results of Experiment 4 suggest a need to support *no awareness* (e.g. no manipulation), *balanced awareness* (e.g. *Dynamic Audio*) and *full awareness* (e.g. *Remove All Audio*) options. Ideally, this *balanced awareness* option would allow the VR user to specify the awareness/presence balance provided. For example, in Experiment 4, the *Dynamic Audio* condition automatically lowered the application audio to 25% of the starting volume but this could be easily configured by the user to a lower or higher value (e.g. 10% or 75%) via system settings to provide a different awareness/presence balance. Applications, such as video games, already allow users to adjust their audio balance (e.g. adjusting the volume of background music, sound effects, dialogue, etc) as an accessibility feature [66, 167] and one can envision how similar systems could enable VR users to define how their awareness of reality is provided.

6.8 Conclusions

Over two lab experiments, Experiments 3 and 4, this chapter investigated how in-VR audio could be manipulated to facilitate verbal interactions between bystanders and VR users.

Experiment 3 investigated automatically decreasing/increasing in-VR audio volume to increase/decrease awareness of a sound event in user's surrounding environment. It found decreasing volume was an effective method of increasing awareness of nearby sound events while increasing volume was ineffective for decreasing awareness of them. Experiment 3 did not, however, evaluate the effectiveness of automatically decreasing volume to facilitate verbal interactions, and only explored one method of manipulating audio. Therefore, Experiment 4 was conducted to investigate the effectiveness of automatically decreasing volume and of removing (either partially or fully) audio elements to facilitate verbal interactions.

Experiment 4 found automatically decreasing in-VR audio volume and the partial/full removal of audio elements could effectively facilitate verbal interactions at the cost of reducing a VR user's sense of presence. This reduced sense of presence, however, did not impact users enjoyment of the VR experience and sentiment towards manipulating in-VR audio to facilitate verbal interactions was positive. Experiment 4 also identified initial insights into participant preferences of how they expected increased awareness to achieved. Most preferred increased awareness be balanced with decreased presence, however, a subset of participants opted to prioritise increased awareness irrespective of the cost to sense of presence.

Combined, the results of Experiments 3 and 4 provide insights into how verbal interactions between bystanders and VR users can be facilitated by manipulating in-VR audio. The results outline multiple methods of manipulating in-VR audio to effectively facilitate verbal interactions between bystanders and VR users: automatically decreasing in-VR audio volume, and the partial/full removal of in-VR audio. This chapter also outlines initial insights into VR user expectations towards how bystander awareness should be increased to facilitate verbal interactions, concluding that, at a minimum, *no awareness*, *balanced awareness* and *full awareness* options should be supported. Ideally, this *balanced awareness* option would allow users to configure the awareness/presence balance provided and future work can explore how/what options should be offered to best accommodate the needs of VR users. The results of Chapter 6 can therefore be used to answer **Research Question 4** as follows:

Research Question 4: *How may in-VR audio be manipulated to facilitate verbal bystander-VR user interactions?*

Given the results from Experiments 3 and 4, the answer to Research Question 4 is that verbal interactions between bystander and VR users can effectively be facilitated by automatically decreasing in-VR audio volume, and partially or fully removing in-VR audio elements. While these methods were effective at facilitating a verbal interaction, they were found to significantly decrease a user's sense of presence in VR. However, this decrease in sense of presence was not said to reduce a user's enjoyment of their experience in VR, and sentiment towards manipulating in-VR audio to facilitate verbal bystander-VR user interactions was positive.

Chapter 7

Awareness Needs During Bystander-VR User Interactions

7.1 Introduction

The chapters of this thesis have investigated thus far: how bystander-VR user interruptions occur and the context of bystander-VR user interactions (Chapters 3 & 4), the design of bystander awareness systems to inform a VR user of a bystander's existence (Chapter 5), and the design of bystander awareness systems to facilitate a verbal bystander-VR user interaction (Chapter 6). Yet, as highlighted in the literature review of this thesis (particularly Section 2.9), at present, we lack a holistic understanding of how disparate works on bystander awareness might be brought together 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 achieves some level of desired increased awareness, and what impact, if any, this has on the VR user's sense of presence (e.g. [6, 9, 56, 21, 20, 23]).

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 by past works, despite outlining many ways in which a VR user's awareness of a bystander can be effectively 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*. Similarly, existing works cannot say how a VR user's awareness of a bystander might vary during a bystander-VR user interaction, or if some single awareness level is sufficient for the duration of any potential interaction. Consequentially, it is therefore necessary that this thesis investigate the real-world applicability of bystander awareness systems by studying how contextual factors, such as the modality of the interaction or the bystander's actions and position relative to the VR user, impact a VR user's preferred choice of bystander awareness approach and awareness needs whilst interacting.

Drawing from the results of the previous chapters of this thesis, this chapter describes a lab experiment, Experiment 5, which investigates the varying need for bystander awareness across fourteen bystander-VR user interaction scenarios. The goal of this experiment was to investigate how contextual factors during a bystander-VR user interaction might influence a VR user's awareness needs of the bystander. The fifth research question of this thesis aims to address this by asking:

- **Research Question 5:** When providing a VR user with increased bystander awareness...
  - **5.1.** what are critical moments when awareness techniques should change?
  - **5.2.** how do awareness needs change at critical moments?

7.1.1 Experiment 5: Overview

To understand how VR user awareness needs vary across bystander interactions, and what motivates changes in awareness needs, an experiment was designed consisting of two parts.

The first part, the *Baseline Usability* evaluation, was designed to familiarise participants with seven bystander awareness systems designed to vary in the extent and detail to which they informed and facilitated bystander co-presence. These were designed based on a review of the literature and the findings of previous chapters of this thesis. A detailed overview of their design is provided in Section 7.2.

In the *Baseline Usability* evaluation participants were introduced to the awareness systems using a game-like task where the usability of the awareness systems and their impact on a user's sense of presence was evaluated. The *Baseline Usability* evaluation was modelled after the methodologies used in prior works (e.g. [6, 20, 21, 23]). This evaluated a breadth of different awareness systems together, enabling a direct comparisons regarding their efficacy.

The second part of the experiment, the *Assessing Awareness Needs* evaluation, then used a novel, think aloud, evaluation methodology to investigate how, when and why participants would use the seven awareness systems to increase their awareness during fourteen bystander-VR user interaction scenarios. The fourteen interaction scenarios were derived from known frequently occurring, real-world interactions between bystanders and VR users. The design of both the *Baseline Usability* and *Assessing Awareness Needs* evaluations are provided in detail in Section 7.3.

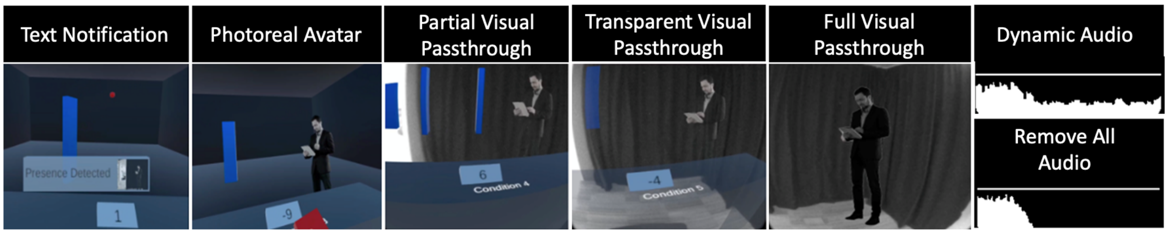


Figure 7.1: The seven designed awareness systems to facilitate bystander-VR user interactions used in Experiment 5. The aural awareness systems are represented by a visualisation of their impact to in-VR audio volume. A full description of these is provided in Section 7.2.

7.2 Experiment 5: Design of the Awareness Systems

Based on a review of the literature, and the findings of Experiments 2, 3, and 4, seven bystander awareness systems were designed that covered the current state of the art, most promising approaches, that varied in the extent and detail to which they inform and facilitate bystander co-presence. The awareness systems (Figure 7.1) are summarised in Table 7.1.

All of the awareness systems were designed to minimise unnecessary exits from VR. All contained identifiable information about the bystander as the results of Experiment 2 indicated some users will exit VR in the absence of this information. All of the approaches were designed to persist 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.

Aurally, *Dynamic Audio* was included as a partial increase of aural awareness and *Remove All Audio* as the aural equivalent of switching to full reality. Experiment 4 found both of these approaches were effective methods of facilitating verbal bystander-VR user interactions.

Visually, a *Text Notification* was included as Experiment 2 reported some VR users consider it sufficient for increasing awareness. A photo of the detected bystander in the surrounding environment was embedded into the text notification (Figure 7.1) to notify the VR user of the bystander's identity and an approximation of their position. This was done to minimise the risk of the *"peeking"* behaviour identified in Experiment 2 from occurring. Also included was a *Photoreal Avatar* of the detected bystander because of the positive results of this approach in a variety of works in the literature [24, 20, 21, 23, 22, 6, 87]. Finally, three variations of passthrough views [92] were included: *Partial Visual Passthrough, Transparent*

Technique	*Description*	*Modality*	*Information Conveyed*	*Examples*
Text Notification	A five 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	[88, 19, 9]
Photoreal Avatar	Augments a photoreal avatar of the bystander into the virtual environment	Visual	Bystander identity Bystander position relative to VR user	[21, 6, 17]
Partial Visual Passthrough	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	[6, 55, 21]
Transparent Visual Passthrough	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	[6, 55, 21]
Full Visual Passthrough	Switch to a full passthrough view and pause the game	Visual	Bystander identity Bystander position relative to VR user Passthrough of surrounding environment	[55, 24]
Dynamic Audio	Automatically lower VR application audio to 25% of the starting volume	Aural	Bystander voice Noise in surrounding environment	Chapter 6
Remove All Audio	Lower all application audio to 0%	Aural	Bystander voice Noise in surrounding environment	Chapter 6

Table 7.1: A summary of the design of the seven bystander awareness systems

Visual Passthrough, and *Full Visual Passthrough*. These augmented increasing amounts of reality into the VR user's virtual environment and were included due to the prevalence of passthrough-based approaches in prior works (e.g. [21, 24, 55, 6]) and commercial VR devices (e.g. [17, 16]). *Full Visual Passthrough* was also included as the visual (and aural) equivalent of switching to a full view of reality without removing the headset.

7.2.1 Awareness System Implementation Details

Wizard of Oz Approach

As in Experiments 3 and 4, and prior works in the literature [24, 20, 22], a wizard of oz [162] approach was used where participants' exposure to the awareness systems in the *Baseline Usability* evaluation was triggered on a timer to simulate bystander detection. In the experiment, all of the awareness systems were said to trigger as soon as the bystander was detected by the VR headset. This wizard of oz approach was used to provide 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 7.3.2.

Fading Awareness In/Out

As in Experiments 3 and 4, to reduce sharp transitions between virtuality and reality which can be disruptive for users [94, 55], all of the awareness systems used a fading effect to add/remove awareness. For *Dynamic Audio* and *Remove All Audio* the same linear interpolation method was reused from Experiments 3 and 4 (Section 6.2.1) to gradually alter in-VR audio volume over a 0.5 second period. For *Photoreal Avatar* the avatar's opacity was faded in/out over a 0.5 second period. For *Partial Visual Passthrough, Transparent Visual Passthrough*, and *Full Visual Passthrough* the content replaced by the augmented passthrough view turned black then faded into the passthrough view over a 0.5 second period. The same effect was used in reverse to return from a view of reality to virtuality. For *Text Notification*, in accordance with Rzayev et al's recommendations [88], the notification spawned in front of the user then moved in closer and followed the user's gaze and then was removed by moving away from the user then disappearing.

The Bystander

For the bystander in the visual conditions, a creative commons video of a man on a green screen was used which was converted to black and white to match the passthrough view of the Meta Quest 2 headset [32] used in the experiment. Chroma key compositing [168] was 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/height. The video involved a bystander who appeared to enter the room, take a few steps, then stop and focus/interact with a tablet they held in their hand. Finally, it should be acknowledged that despite participants being instructed to act as if they knew the bystander in the video (e.g. to pretend they were a friend they lived with) that ultimately they did not. As such, this is a limitation of the approach taken as participants may have responded differently had they truly known the bystander. A second limitation of this approach was the reuse of the same video clip across every condition of the experiment. While beneficial for experimental repeatability, this may have appeared less natural to participants than an individual who repeating the same actions/gestures uniquely each time but with natural, subtle differences in their movement.

7.3 Experiment 5: Study Design

The experiment 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. [169]).

The first part of the experiment, the *Baseline Usability* evaluation, was designed to familiarise participants with the awareness systems and to evaluate their usability and impact on sense of presence. This provided an objective assessment of the awareness systems enabling direct comparisons regarding their efficacy. The design of its experimental task is provided in Section 7.3.1, conditions in Section 7.3.2, and evaluation measures used in Section 7.3.3.

The second part of the experiment, the *Assessing Awareness Needs* evaluation, was designed to capture how participants would use a variety of awareness systems (each providing differing degrees of reality awareness) across a range of bystander-VR user interaction scenarios. The design of the think aloud task used to conduct the *Assessing Awareness Needs* evaluation and the interaction scenarios used within the task are provided in Sections 7.3.5 and 7.3.6.

Finally, the apparatus used to conduct the experiment is summarised in Section 7.3.7, and the experimental procedure in Section 7.3.8.

7.3.1 Baseline Usability Evaluation: Experimental Task

The experimental task used in the *Baseline Usability* evaluation was a modified version of the game-task developed for Experiment 4 (described in detail in Section 6.5.1). This task was reused as it was a suitable recreation of the affordances and visual/aural demand of home VR entertainment [33, 36]. It also provided a usage scenario requiring high levels of attention demand and engagement from the VR user, which would consequentially stress the usability of the awareness systems being evaluated. The modifications made to the game/task from Experiment 4 are as follows:

- The experimenter sat behind the VR user. This was to ensure the experimenter was outside the VR user's direct line of sight in the passthrough view conditions.
- The game session lengths (exposure times to each condition) were modified to accommodate the increased number of conditions and change in experiment length. The changed times are outlined in full in Section 7.3.2.

7.3.2 Baseline Usability Evaluation: Conditions

The *Baseline Usability* evaluation had eight conditions: one for each of the seven awareness systems (described in Section 7.2) and a *Baseline* condition (no awareness system). The *Baseline Usability* evaluation consisted of two 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, one condition (one session of the game) lasted forty-five seconds with twenty-five seconds exposure to the awareness system (starting after ten seconds). Before starting each condition, participants were introduced to the condition (e.g. *"This is the photoreal avatar, the detected bystander will appear in the VR scene with you"*).

The *evaluation phase* assessed each condition, during which one condition lasted ninety seconds with sixty seconds exposure to the awareness system (starting after twenty seconds). After each condition ended the participant removed the headset and completed a questionnaire. Condition order was counterbalanced using a eight condition fully balanced Latin square approach.

7.3.3 Baseline Usability Evaluation: Questionnaire Measures

A questionnaire was designed, based on similar evaluations in prior works [6, 21, 20, 9], to evaluate the awareness systems' usability and impact on sense of presence. All questions used a 7-point Likert scale. The usability questions were not asked for the *Baseline* as the questions were not applicable.

- ***Usability Questions:*** evaluated usability using eight 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:*** evaluated presence using the (1) *"Sense of Being There"* and (2) *"Involvement"* subsets of the IPQ questionnaire [46] and the following question: (3) *"How much did it seem as if you and the person you saw/heard were together in the same place?"* from the TPI questionnaire [170] (1=not at all, 7=very much).

7.3.4 Design of the Assessing Awareness Needs Evaluation

While the *Baseline Usability* evaluation investigated the usability of the designed 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 participants would use the awareness systems experienced to increase their awareness during fourteen bystander-VR user interaction scenarios.

To guide this investigation, four factors were chosen to design the interaction scenarios around to explore if/how a VR user's awareness needs are influenced. The four factors were:

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

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

7.3.5 Assessing Awareness Needs Evaluation: Experimental Task

To ensure the scenarios used in the evaluation were realistic, the fourteen interaction scenarios were derived from known, frequently occurring, real-world interactions between bystanders and VR users. These were informed by the findings of Survey 2 of this thesis (Section 4.3) and from prior works [7, 10, 111, 84, 9, 18, 72, 11].

The interaction scenarios described co-existing, verbal/non-verbal interactions occurring inside/outside of the VR user's play area (the predominant types of bystander-VR user interactions which occur in-the-wild as identified by Survey 2). Eight 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. Three scenarios were unique interactions to explore bystander actions of interest, and three 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 interaction 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 two to five 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"*. Similarly, 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 7.2 summarises the interaction scenarios.

7.3.6 Assessing Awareness Needs Evaluation: Captured Data

For each step of every interaction scenario participants were tasked with selecting their awareness preference from the seven awareness systems they experienced in the *Baseline Usability* evaluation (Section 7.2), in addition to the options of *"No Awareness"*, if they did not want any awareness system, and to *"Remove The Headset"* if they wanted to take off the headset. Participants who selected *Remove The Headset* were given the option of *"Put The Headset Back On"* in subsequent steps, however, no participant selected this during the experiment.

Participants could combine awareness options (e.g. select *Photoreal Avatar* and *Dynamic Audio*) but were required to rank their selected options by priority if they selected multiple.

Scenario	Description	Motivated By
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)*	*Survey 2,* [84, 18]
INSIDE-TV	A bystander, inside the play area, who ignores the VR user whilst watching TV *(#3 steps)*	*Survey 2,* [7, 84, 18]
OUTSIDE-PHONE	A bystander, outside the play area, who ignores the VR user whilst using their smartphone *(#2 steps)*	*Survey 2,* [84, 18]
INSIDE-PHONE	A bystander, inside the play area, who ignores the VR user whilst using their smartphone *(#3 steps)*	*Survey 2,* [7, 84, 18]
OUTSIDE-SHORT-VERBAL	A bystander, outside the play area, who verbally interacts with the VR user *(#2 steps)*	*Survey 2,* [9, 18]
INSIDE-SHORT-VERBAL	A bystander, inside the play area, who verbally interacts with the VR user *(#3 steps)*	*Survey 2,* [9, 18]
OUTSIDE-LONG-VERBAL	A bystander, outside the play area, who first ignores the VR user then verbally interacts with them *(#4 steps)*	*Survey 2,* [9, 18]
INSIDE-LONG-VERBAL	A bystander, inside the play area, who first ignores the VR user then verbally interacts with them *(#5 steps)*	*Survey 2,* [9, 18]
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)*	*Survey 2,* [10, 6, 7]
SILENT-OBSERVER	A bystander, outside the play area, silently watching the VR user *(#2 steps)*	*Experiment 1,* [10, 7]
FILMING-BYSTANDER	A bystander, outside the play area, filming the VR user with their smartphone without permission *(#2 steps)*	*Experiment 1,* [11]
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)*	*Survey 2,* [72]
MULTIPLE-BYSTANDERS	Multiple bystanders enter the room *(#2 steps)*	*Survey 2,* [7, 72]
UNRECOGNISED-BYSTANDER	The bystander who enters the room is not recognised by the VR user *(#2 steps)*	*Survey 1,* [76]

Table 7.2: A summary of the interaction scenarios used in the *Assessing Awareness Needs* evaluation. The steps associated with each scenario are provided in full in Section 7.6.

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 two scenarios acted as a tutorial where the experimenter guided the participant through completing the scenarios (e.g. explaining the UI of the survey application used to record their choices, prompting them with questions to assist with the think aloud process). After this, the remaining twelve scenarios were presented in a randomised order.

7.3.7 Apparatus

A Meta Quest 2 headset [32] was used to conduct the experiment. The Quest 2's on-board, acoustically transparent [120], audio system was used in all of the conditions. A Google Pixel 4a [171] was used by the experimenter to record, and transcribe, participants' think aloud comments.

7.3.8 Procedure

Upon arrival the experiment's purpose was explained and a consent form and a demographic questionnaire were given to the participant. It was explained the experiment would consist of two parts and that each would be explained in detail prior to conducting it.

The *Baseline Usability* evaluation was then explained to the participant. Participants were told they would play a VR game and experience seven awareness systems designed to increase their awareness of a nearby non-VR person (a bystander). Participants were told they would see this bystander in several conditions and that they were to assume it represented a known person to them (e.g. a friend they lived with). A demonstration video[1] of the game was then shown and its controls explained. Participants were then instructed where to stand and shown (if required) how to put on and wear the headset.

Participants then began the training phase of the *Baseline Usability* evaluation, during which they were told to set the headset's system volume to a comfortable but immersive level. Most set the 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 the conditions, participants were asked to rank order the awareness systems from best to worst (without a specific metric) and were then asked to describe how they ranked their preferences (e.g. by which metric).

Upon completing the *Baseline Usability* evaluation, after a short break, the *Assessing Awareness Needs* evaluation was explained. Participants were told they would be presented with fourteen descriptions of bystander-VR user interactions broken down into a series of steps. In these, participants were told to imagine they were the VR user playing a game similar to the one they had just experienced in the experiment'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 (e.g. one with open floor space for dedicated VR use but with furniture outside of the VR user's play area such as a couch and TV). Participants were told their task was to select the amount of real world awareness, based on the awareness systems they had experienced in the *Baseline Usability* evaluation, they wanted to experience for each step of the described interaction scenarios. 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 the *"no awareness"* and *"take off headset"* options whenever desired and that the task was designed to simply capture their own ideal awareness options. Participants were instructed to think aloud during

[1] `https://youtu.be/pP-ORj49XWU`

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 experiment took on average sixty minutes to complete (approximately thirty minutes for each part). Upon completing the study participants were compensated for their time with a £10 Amazon voucher.

7.4 Experiment 5: Results Overview

To aid readability, the results of the *Baseline Usability* evaluation and *Assessing Awareness Needs* evaluation are separated into two sections. The *Baseline Usability* evaluation results are presented in Section 7.5. The *Assessing Awareness Needs* evaluation results are presented in Section 7.6.

7.4.1 Participants

Participants were recruited using social media and university mailing lists. 16 participants (5 female, 11 male) completed the experiment. Participants ranged in age from 19 to 33 (M=23.13, SD=3.70). Participants were asked to indicate their prior experience with VR headsets using a 5-point Likert scale (1=none, 5=a lot), (M=4.00, SD=1.10). All reported they had at least *"a little (2)"* prior experience with VR.

7.5 Experiment 5: Baseline Usability Results

7.5.1 Analysis

For the Likert-scale questions the mean and standard deviation values was calculated. A Friedman test was used to find significant differences between factors and was followed by pairwise comparisons using Wilcoxon signed-rank tests with Bonferroni corrected p-values. For participants' preference ranking, the average ranking score was calculated for each condition using the rankings given. Participants' comments, used to justify their ranking, were coded using selective coding [121] where participants' statements were assigned emergent codes over repeated cycles with the codes grouped using a thematic approach. A single coder performed the coding and reviewed/discussed the coding with one other researcher. Two coding cycles were performed.

Usability Factor	*(1) Text Notification*	*(2) Photoreal Avatar*	*(3) Partial Visual Passthrough*	*(4) Transparent Visual Passthrough*	*(5) Full Visual Passthrough*	*(6) Dynamic Audio*	*(7) Remove All Audio*	***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 (0.60)	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 (1.90)	6.00 (1.70)	3.19 (1.51)	2.94 (1.78)	$\chi^2(6) = 27.54$, $p<0.0024$	5-6, 5-7
Felt natural	3.00 (1.70)	4.88 (1.76)	4.5 (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 (0.70)	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 (1.50)	2.31 (0.98)	4.25 (2.02)	4.62 (1.93)	5.31 (2.08)	2.81 (1.84)	3.00 (1.80)	$\chi^2(6) = 26.50$, $p<0.0024$	1-5, 2-4, 2-5

Table 7.3: Experiment 5's mean (standard deviation) values, and significant differences, for the usability questions in the *Baseline Usability* evaluation.

7.5.2 Usability Evaluation Results

The mean, standard deviation values and Friedman test results of the usability questions are summarised in Table 7.3. The results of Wilcoxon signed-rank pairwise comparisons, where applicable, are also summarised in Table 7.3. Each usability question is discussed, in turn, below.

Disruptive

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

Frustrating

The conditions scored similarly in terms of their frustration caused as they did disruption. Generally, the more reality incorporated into the virtual environment the more frustrating the condition was said to be. Again, *Text Notification* was the exception to this, with participants again citing their difficulty ignoring it to be frustrating. However, unlike disruption, only two significant differences were found between the conditions: between *Dynamic Audio* and *Text Notification*, and between *Dynamic Audio* and *Full Visual Passthrough*. These were significant differences between the two most frustrating conditions (*Text Notification* and *Full Visual Passthrough*) and the least frustrating condition (*Dynamic Audio*). *Full Visual Passthrough* again scored highest with participants citing the forced switch to reality to be their main issue with it.

Urgency

The visual awareness systems were considered more urgent than the aural systems. Within the passthrough approaches (*Photoreal Avatar, Partial Visual Passthrough, Transparent Visual Passthrough, Full Visual Passthrough*), the greater amount of reality incorporated the more urgent the approach was said to be (e.g. *Photoreal Avatar* was not considered particularly urgent whereas *Full Visual Passthrough* was). *Text Notification* was the second most urgent condition which participants attributed to its unavoidable nature. Two significant differences were found: between *Full Visual Passthrough* and *Dynamic Audio* and between *Full Visual Passthrough* and *Remove All Audio*.

Natural

All conditions, except for *Text Notification*, were said to be natural methods of increasing awareness. Participants said *Text Notification* 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 abstract pop-up"*. Only one significant difference was found: between *Text Notification* and *Dynamic Audio*, the least (*Text Notification*) and most (*Dynamic Audio*) natural conditions.

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 the participants understood the awareness systems, reinforcing the results of the *Assessing Awareness Needs* evaluation where participants use of the awareness systems was assessed.

Informative

All approaches were considered informative and no significant differences were found between any of the conditions. Generally, the passthrough approaches (*Photoreal Avatar, Partial Visual Passthrough, Transparent Visual Passthrough, Full Visual Passthrough*) were considered more informative than the others. Although this is expected, to a degree, due to the type of information about the bystander and surrounding area relayed by the passthrough approaches compared to the others.

Improved Communication

All of the awareness systems, apart from *Text Notification*, were said to improve communication with a bystander. That *Text Notification* did not suggests participants did not consider notification of bystander existence alone sufficient for improving communication, particularly relative to the other awareness systems. 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. However, both the aural awareness systems were also considered effective methods of improving communication. Four significant differences were found: between *Text Notification* and *Transparent Visual Passthrough, Full Visual Passthrough, Dynamic Audio, Remove All Audio*.

Too Aware of the Real World

Text Notification, Photoreal Avatar, Dynamic Audio and *Remove All Audio* were not said to make participants too aware of the real world whereas *Partial Visual Passthrough, Transparent Visual Passthrough* and *Full Visual Passthrough* were. Three significant differences were found: between *Text Notification* and *Full Visual Passthrough*, between *Photoreal Avatar* and *Transparent Visual Passthrough* and between *Photoreal Avatar* and *Full Visual Passthrough*.

7.5.3 Sense of Presence Evaluation Results

The mean, standard deviation values and Friedman test results of the sense of presence questions are summarised in Table 7.4. The results of Wilcoxon signed-rank pairwise comparisons, where applicable, are also summarised in Table 7.4.

For *IPQ: Sense of Being There*, all conditions scored similarly with no significant differences being between them (Table 7.4). For *IPQ: Involvement*, ten significant differences were found between the conditions. These were differences between: the baseline and *Partial Visual Passthrough, Transparent Visual Passthrough, Full Visual Passthrough, Dynamic Audio, Remove All Audio*, between *Text Notification* and *Transparent Visual Passthrough, Full Visual Passthrough, Dynamic Audio*, and between *Photoreal Avatar* and *Transparent Visual Passthrough, Full Visual Passthrough*. Generally, *IPQ: Involvement* decreased as increasing amounts of reality were augmented into the virtual environment. Noteworthy also is that there was no significant difference between *Baseline* and *Text Notification*. This highlights that despite *Text Notification* being considered disruptive and frustrating to the VR experience that this did not significantly impact presence in VR.

For *Togetherness in the Same Space*, all of the awareness systems, expect for *Text Notification*, were perceived as increasing feelings of togetherness between the VR user and bystander. Ten significant differences were found between the conditions. These were significant differences between: the baseline and *Photoreal Avatar, Partial Visual Passthrough, Transparent Visual Passthrough, Full Visual Passthrough, Dynamic Audio, Remove All Audio* and between *Text Notification* and *Partial Visual Passthrough, Transparent Visual Passthrough, Full Visual Passthrough, Dynamic Audio*.

7.5.4 Preference Ranking Results

The average ranking score of participants preference ranking of the awareness systems is shown in Table 7.5 where a higher average ranking score indicates a higher preference towards an approach.

Dynamic Audio scored highest (5.06 out of 7.00) and was the first choice of 5 participants.

Sense of Presence	*(0) Baseline*	*(1) Text Notification*	*(2) Photoreal Avatar*	*(3) Partial Visual Passthrough*	*(4) Transparent Visual Passthrough*	*(5) Full Visual Passthrough*	*(6) Dynamic Audio*	*(7) Remove All Audio*	***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 7.4: Experiment 5's mean (standard deviation) values, and significant differences, for the presence questions in the *Baseline Usability* evaluation. A higher score indicates a greater sense of presence/togetherness).

Condition / Ranking	*1st*	*2nd*	*3rd*	*4th*	*5th*	*6th*	*7th*	***Average Ranking***
Dynamic Audio	5	1	3	6	0	0	1	5.06
Partial Visual Passthrough	2	4	4	2	2	1	1	4.69
Photoreal Avatar	1	4	5	0	4	2	0	4.50
Transparent Visual Passthrough	4	2	2	2	2	3	1	4.44
Remove All Audio	1	5	1	2	5	2	0	4.31
Text Notification	3	0	1	1	1	4	6	2.94
Full Visual Passthrough	0	0	0	3	2	4	7	2.06

Table 7.5: The average ranking scores (of a possible 7.0) from the preference ranking of the awareness systems in Experiment 5 where a higher score indicates a higher preference towards an approach. *Dynamic Audio* was the preferred approach, while *Text Notification* and *Full Visual Passthrough* performed worst.

Text Notification (2.94 out of 7.00) and *Full Visual Passthrough* (2.06 out of 7.00) performed worst, a result in-line with their scores 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"*.

7.5.5 Summary of the Baseline Usability Results

The results of the *Baseline Usability* evaluation validate that the 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, *Dynamic Audio, Photoreal Avatar, Partial Visual Passthrough* performed well and scored highest in participants rankings. Meanwhile, *Text Notification* performed poorly and was considered the second most frustrating/disruptive approach, the least natural approach, tied least informative approach, was not said to improve communication with the bystander, and ranked second lowest in participants rankings. Therefore, if VR users were to determine awareness choices based on the usability of an awareness system, from the results of the *Baseline Usability* evaluation, one would expect awareness to predominantly be provided by *Dynamic Audio, Photoreal Avatar, Partial Visual Passthrough* and for participants to avoid *Text Notification* which performed significantly worse.

7.6 Experiment 5: Assessing Awareness Needs Results

7.6.1 Analysis

First, participants responses to each interaction scenario were quantitatively analysed. Each awareness modality was analysed separately. An average awareness score for each step of every interaction scenario was calculated. This was calculated by assigning each awareness option a rank ordered by the extent to with it increased awareness.

For the aural awareness options this ranking was:

- *No Awareness: 1, Dynamic Audio: 2, Remove All Audio: 3*

For the visual awareness options this ranking was:

- *No Awareness: 1, Text Notification: 2, Photoreal Avatar: 3, Partial Visual Passthrough: 4, Transparent Visual Passthrough: 5, Full Visual Passthrough: 6, Take Off Headset: 7*

These rankings were used to calculate, for each step of every interaction scenario, the mean and standard deviation awareness scores (Tables 7.6, 7.8, and 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 (with Bonferroni corrected p-values if required).

To further investigate how awareness needs varied, *"rate of change"* values were calculated, for each step of every interaction scenario, to summarise the number of participants increasing, maintaining or decreasing their awareness needs relative to their selected awareness levels for the previous step in the interaction scenario. For example, *(Visual Awareness - Increasing: 50.00%, Maintaining: 25.00%, Decreasing: 25.00%)* meant, for the given step, 50.00% of participants increased awareness relative to the previous step, 25.00% maintained prior levels of awareness and 25.00% decreased awareness.

This quantitative analysis of every interaction scenario was used to reinforce the results of a selective coding [121] of participants' comments made while discussing their choice of awareness options, their expectations for how, when and why bystander awareness should be increased and their general attitudes towards awareness of bystanders. Participants' comments were assigned emergent codes over repeated cycles with the codes grouped using a thematic approach. A single coder performed the coding and reviewed/discussed the coding with two other researchers. Two coding cycles were performed.

Finally, to demonstrate the trajectory of participants changing awareness needs for a given scenario, a visualisation was created of the *INSIDE-LONG-VERBAL* scenario (Figure 7.2). This visualisation, shows traces of individuals' choices made at each step of the scenario. However, as this is an unexplored visualisation approach, and future work beyond the scope of this thesis is need to investigate it further, only the *INSIDE-LONG-VERBAL* scenario was visualised as an example to demonstrate the trajectory of participants choices.

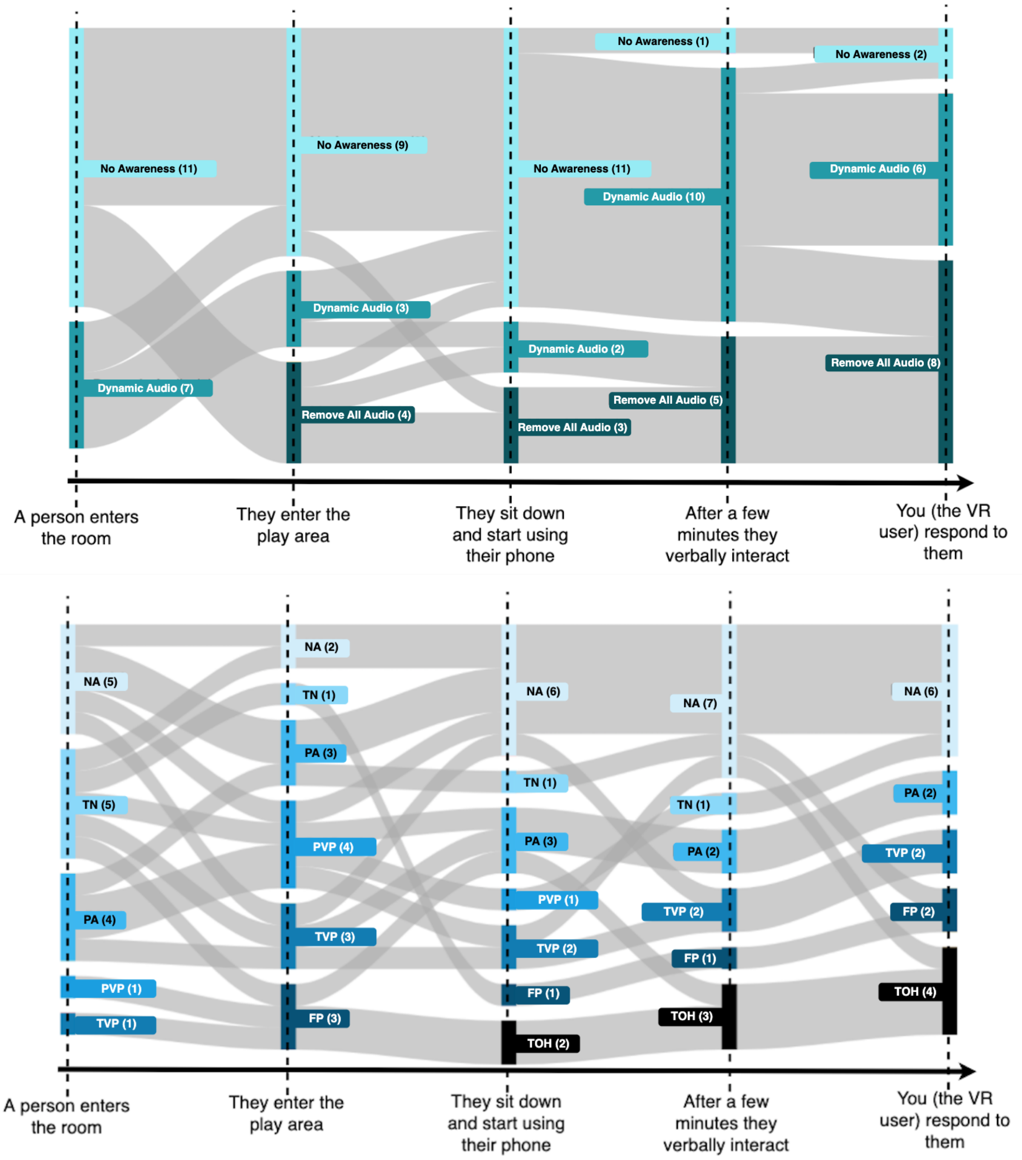


Figure 7.2: Examples visualisations showing the flow of each participants choice of aural and visual awareness for the *INSIDE-LONG-VERBAL* scenario. The upper visaul shows aural awareness, the lower visual awareness. In the visual awareness graphic, *NA: No Awareness, TN: Text Notification, PA: Photoreal Avatar, PVP: Partial Visual Passthrough, TVP: Transparent Visual Passthrough, FP: Full Visual Passthrough, TOH: Take of Headset.*

7.6.2 VR User Awareness Needs at the Initial Point of Bystander Contact/Detection

To investigate VR user awareness needs at the initial point of bystander contact a consistent first step was used across all fourteen 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 interaction scenario was the same as their selection for it in the last interaction scenario. It was hypothesized participants may, after being exposed to range of possible bystander-VR user interactions, change their awareness preferences for this initial 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: mean=1.25, SD=0.43, Increasing=25.0%, Maintaining=75.0%, Decreasing=N/A* and *Visual Awareness: mean=2.25, SD=1.15, Increasing=68.75%, Maintaining=31.25%, Decreasing=N/A*) reinforces participants prioritised visual awareness and suggests they wanted low general levels of bystander awareness at this step.

Examining the chosen awareness option(s), for aural awareness, all 4 participants chose *Dynamic Audio* believing it was most appropriate, *P2: "it still gives you some immersion"*. For visual awareness, 9 participants selected less intrusive approaches (*Text Notification: 5, Photoreal Avatar: 4*) believing they were sufficient as initial increases of awareness, *P3: "It tells you someone's there and who they are"*. However, 2 participants selected the passthrough view approaches (*Partial Visual Passthrough: 1, Transparent Visual Passthrough: 1*) wanting awareness of their surrounding environment in addition to the bystander, *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 *Text Notification* said they wanted a continuous 1-to-1 relay of the bystander's position relative to their own.

7.6.3 How VR User Awareness Needs Varied After Initial Bystander Contact/Detection

After completing the *Assessing Awareness Needs* evaluation, participants were asked to reflect on how they, generally, 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, was used to create a categorisation of attitudes for how a VR user's awareness should be provided during an interaction with a bystander. This resulted in four personas outlining how participants, generally, expected bystander awareness to be provided:

(1) Incrementally Adjust Awareness: 6 participants wanted to initially increase awareness to some starting point and then for awareness to incrementally adjust contextually throughout the interaction. For example, if the participant selected *Photoreal Avatar* when the bystander entered the room, if the bystander entered the play area then awareness would increase to *Dynamic Audio* and *Partial Visual Passthrough*. Participants believed such incremental adjustments was the best compromise for increasing awareness whilst retaining immersion in VR and would be 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 to contextually prioritise low/high awareness states throughout the interaction. For example, participants selected *Text Notification* when the bystander entered the room but if the bystander entered the play area would increase awareness to *Full Visual Passthrough*. Similarly, participants wanted decreases of awareness to be comparably sudden (e.g. decreasing from *Full Visual Passthrough* to *Text Notification*). Participants wanted this behaviour as they believed such sudden changes in awareness was the best approach for focusing attention on what was contextually most important, either 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"*.

Motivations for Changing Awareness Needs

While the above personas outline how VR users, generally, expect bystander awareness to be provided, the *Assessing Awareness Needs* evaluation was designed to investigate how several bystander characteristics motivated a change in desired levels of bystander awareness. The subsequent subsections of this results section explore these characteristics in-depth, and can be summarised as how a VR user's bystander awareness needs are influenced by:

- The bystander's position relative to the VR user (Section 7.6.4)
- The bystander's actions and engagement with the VR user (Section 7.6.5)
- The type of bystander with whom the VR user is interacting (Section 7.6.6)

7.6.4 The Influence of a Bystander's Position on Awareness Needs

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 a consistent step was used, *"They enter the VR user's play area"*, in all five interaction scenarios involving a bystander-VR user interaction inside of the VR user's play area. Participants consistently selected the same awareness option(s) for all occurrences of this step. Again, it was hypothesized participants may change awareness preferences for this step as the task progressed. However, again 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=25.00%, 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=25.00%, Maintaining=68.75%, Decreasing=6.25%*

- *Visual Awareness: M=3.88, SD=1.58, Increasing=75.00%, 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 Friedman test reported no significant difference between the participants response to the *"A person enters the room"* and *"They enter the play area"* steps ($\chi^2(1) = 0.56$, $p=0.45$). For visual awareness, a Friedman test reported a significant difference between participants response to the *"A person enters the room"* and *"They enter the play area"* steps ($\chi^2(1) = 7.56$, $p<0.05$) and a Wilcoxon signed-rank test confirmed a significant difference ($p<0.05$).

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 *(Text Notification: 1, Photoreal Avatar: 3, Partial Visual Passthrough: 4, Transparent Visual Passthrough: 3, Full Visual Passthrough: 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 *(Text Notification: 1, Dynamic Audio 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.

Awareness Needs for the Same Interaction Inside/Outside the VR User's Play Area

Four pairs of inside/outside interaction scenarios were included to investigate the same bystander-VR user interaction occurring inside and outside of the play area (Table 7.6). 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 any 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 7.6. The difference between the pairs is most prominent in desired visual awareness. For example, consider 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%*
- *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 7.6. Greater levels of desired awareness are also highlighted by participants choice of awareness option(s) across the scenarios (Table 7.7). 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. *Partial Visual Passthrough, Transparent Visual Passthrough, Full Visual Passthrough*).

7.6.5 The Influence of a Bystander's Actions on Awareness Needs

VR User Awareness Needs With a Interacting Bystander

During scenarios involving interacting bystanders (e.g. verbal bystander-VR user interactions: *INSIDE-SHORT-VERBAL, OUTSIDE-SHORT-VERBAL, INSIDE-LONG-VERBAL, OUTSIDE-LONG-VERBAL*) participants prioritised the awareness modality which best fit the on-going interaction. That is, during any verbal exchanges they prioritised increasing aural awareness and prioritised visual awareness when not verbally interacting (Table 7.6).

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 disagreed stating, for the proposed scenarios, shouting over in-VR audio would suffice. Attitudes towards visual awareness during verbal exchanges was more

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 7.6: The mean/standard deviation values and rate of change percentages 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.

Condition	% of Selected Steps (Inside Pairs)	% of Selected Steps (Outside Pairs)
AURAL AWARENESS		
No Awareness	53.13	58.75
Dynamic Audio	25.89	30.63
Remove All Audio	20.98	10.63
VISUAL AWARENESS		
No Awareness	28.57	55.00
Text Notification	13.39	17.50
Photoreal Avatar	18.30	13.75
Partial Visual Passthrough	10.71	4.38
Transparent Visual Passthrough	11.61	5.00
Full Visual Passthrough	9.82	1.25
Take Off Headset	7.59	3.13

Table 7.7: The frequency of chosen awareness options, relative to the number of possible steps, for the *PAIR SCENARIOS*, showing greater visual awareness needs when inside of the play area. Heatmaps range from white (lowest) to purple (highest) based on the frequency.

varied. 6 participants said visual awareness was unnecessary, *P1 : "I don't need visual information just hear [the verbal interaction]"*. 5 said it was essential to see facial expressions and body language, *P8: "I want to see how they are reacting to what I'm saying"*. 5 wanted balanced levels of visual/aural awareness so felt some visual awareness was appropriate.

All participants said longer verbal exchanges would increase their desired visual awareness (and the likelihood that 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, they would exit VR.

VR User Awareness Needs With a Non-Interacting Bystander

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 7.6) 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 that an active bystander (e.g. one with a lot of movement around and interaction with the surrounding environment) justified higher levels of bystander aware-

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 7.8: The mean / standard deviation values and rate of change percentages 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*).

ness. This difference 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 7.6) while in *DUSTING-BYSTANDER* wanted high levels of both aural and visual awareness (Table 7.8). 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"*.

VR User Awareness Needs When Privacy is Encroached Upon

Participants wanted increased awareness of any bystander they percieved to encroach on their privacy. This is shown by comparing the *SILENT-OBSERVER* and *FILMING-BYSTANDER* scenarios (Table 7.8). 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"*.

7.6.6 The Influence of the Type of Bystander on Awareness Needs

The bystander with whom the interaction was occurring was found to influence the VR user's awareness needs. Three scenarios (*UNRECOGNISED-BYSTANDER, MULTIPLE-BYSTANDERS, DOG-BYSTANDER*) were designed to explore this by investigating changes in desired awareness should the bystander differ from the *"single, known bystander"* used in all the other interaction scenarios. Table 7.9 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*).

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 7.9: 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.

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 (*Full Visual Passthrough:* 1, *Take Off Headset:* 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 (*Full Visual Passthrough:* 2, *Take Off Headset:* 7). All said this was necessary to ensure their safety and because they did not feel comfortable continuing to use VR in this context. 6 participants increased visual awareness but remained in VR (*Text Notification: 2, Partial Visual Passthrough: 3, Transparent Visual Passthrough: 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 their 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 (*Full Visual Passthrough:* 2, *Take Off Headset:* 11) to investigate who the bystander was. The 3 participants who opted not switch to reality instead increased only their visual awareness (*Photoreal Avatar:* 1, *Partial Visual Passthrough:* 2) and justified this by stating their chosen approach relayed sufficient information to them.

7.6.7 Summary of Assessing Awareness Needs Results

To close, this results section summarises key findings with regards to the four factors the *Assessing Awareness Needs* evaluation was structured around. For *Initial & Prolonged Contact*, the results report most VR users want to be informed informed visually of a bystander's existence at the initial point of bystander contact/detection. Although it should be noted that there was a variety of opinions regarding how this increased awareness should be achieved (e.g. some VR users preferring *Text Notifications* while others preferred *Photoreal Avatar*, etc). Crucially, however, the results demonstrate that VR user awareness needs are dynamic and are expected to change contextually relative to the demands of the bystander-VR user interaction. For *Encroachment*, the results 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 *Activity*, the results show most VR users prioritise the awareness modality which best fits the current interaction (e.g. prioritising increased aural awareness during verbal exchanges). Finally, for *Bystander Type*, the results confirm that 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"*).

7.7 Experiment 5: Discussion

7.7.1 Establishing the Need for Socially Intelligent Bystander Awareness Systems

The results of Experiment 5 show that VR users expect bystander awareness to vary over the course of an interaction with a bystander. Four personas are outlined (Section 7.6.3) which demonstrate empirically, for the first time, how VR users expect awareness of bystanders to dynamically change based on the demands of their interaction with a bystander. Additionally, the results show that no single awareness system 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).

The results of Experiment 5 develop 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 informing a VR user of bystander co-presence or increasing VR user safety [15, 7, 9] 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 [6] or within some distance of the VR user (Chapter 5)). 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 [146, 56], or context awareness methods [85, 86] 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 [78]. 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.

7.7.2 What Drives Awareness: Critical Moments and Context

From the results of Experiment 5, three ***critical moments*** during bystander-VR user interactions can be derived which elicit a significant change in a VR user's awareness needs: *(M1) the initial point of bystander contact*, *(M2) bystander entry into the VR user's play area*, and *(M3) a verbal exchange between the VR user and bystander*. These are emergent moments within a bystander-VR user interaction which elicit a significant change in a VR user's awareness needs with respect to desired degree of bystander awareness provided, or even a switch in the prioritised awareness modality. While one expects these 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*, the results of Section 7.6.2 show a clear desire for increased (visual) bystander awareness. This verifies VR users want VR headsets to be equipped with awareness systems to notify them of bystander existence. It also demonstrates that a range of awareness systems, each relaying different amounts of bystander awareness, are required to accommodate the varying needs of VR users (reaffirming the results of Chapters 5 and 6). Similarly, at *(M2) bystander entry into the play area*, the results (Section 7.6.4) show a desire for visual bystander awareness through an awareness system that continuously relay the bystander's position relative to the VR user. This builds on findings from Experiment 2 and demonstrates that higher desired baseline levels of bystander awareness are needed for an interaction inside of a VR user's play area compared to the same interaction occurring outside of it.

Crucially, 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* (Section 7.6.5), 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 (*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.

7.7.3 Where Existing Evaluation Methodologies of Bystander Awareness Systems Fall Short

Experiment 5's results demonstrate also that VR users do not manage bystander awareness based solely on the usability of awareness systems. This result is most clearly demonstrated by the response to *Text Notification* across the *Baseline Usability* and *Assessing Awareness Needs* evaluations. In the *Baseline Usability* evaluation, *Text Notification* 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. If participants opted to use awareness systems based on their usability, the results of the *Baseline Usability* evaluation indicate that the *Text Notification* would not be used frequently due to this poor performance.

However, in the *Assessing Awareness Needs* evaluation, *Text Notification* was the second most frequently selected visual awareness system. Participants justified their selection of *Text Notification* 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."*.

This demonstrates that VR users use of bystander awareness systems is not dictated solely by the usability of an awareness system or its impact on sense of presence. Initial insights of this were captured in Chapters 5 and 6 where some participants indicated a preference towards awareness systems which caused greater levels of disruption but provided greater levels of bystander awareness (or vice versa). The results of Experiment 5 demonstrate this directly and show a VR user's decision to use one awareness system over another is a complex trade-of for VR users between desired awareness, immersion, contextual factors (e.g. individual priorities when interacting, safety and privacy concerns, the position/actions of the bystander, etc). This, crucially, highlights a shortcoming with the evaluation approaches used in the literature (e.g. [20, 21, 6, 55, 24, 23]) which predominantly test whether a given awareness system can increase awareness and what impact this has on the user's sense of presence. They do not, however, consider how disparate approaches towards increasing awareness might be used, which the results of Experiment 5 show the need to do.

7.7.4 The Need for New Approaches to VR User-Bystander Interaction Research

The contradictions seen between the *Baseline Usability* and *Assessing Awareness Needs* results necessitate a reflection on the prevailing methodology of assessing bystander awareness systems in HCI research. A typical, well-replicated approach (e.g. [6, 9, 20, 21, 56, 15, 55]) 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 [21, 20, 87] in a lab context. Most evaluations explore the moment a bystander enters the room and interrupts the VR user (e.g. [6, 24, 9, 15]).

Based on the findings of Experiment 5, such an evaluation approach may produce misleading and inaccurate recommendations (e.g. discounting *Text Notification*). This is because there is no holistic consideration that awareness needs vary significantly based on the interaction context, undermining the ecological validity of such evaluations. Therefore the recommendation is made that we, as a community, (a) consider alternate evaluation methodologies that can take into account *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, Section 7.7.2 outlines a three critical moments that should be considered during bystander awareness system evaluations. The suggestion is made that such critical moments be incorporated into evaluation scenarios (e.g. through in-situ evaluations, acted out bystander interactions, nested simulated realities [172, 49]), 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 the *Assessing Awareness Needs* evaluation design). Whilst such critical moments will be refined and expanded upon by future works, they are nonetheless a first promising step towards improving the ecological validity of such evaluations.

Regarding integrative research that supports cross-comparison of awareness systems, consideration should also be given to how research in other XR specialisms has facilitated integrative works. For example, Luca et al's *"Locomotion Vault"* [163] shows how 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.

7.7.5 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 a bystander and VR user during an interaction may be significantly engaged, many works have developed systems to enable an individual (e.g. a co-located VR user [87], a co-located augmented/mixed reality user [137, 173, 174], or a co-located non-HMD user [111, 175, 176]) 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 [87, 15] or to facilitate verbal interactions (Chapters 4 and 6)), systems designed to enable collaborative cross-reality interactions have their own unique challenges and expectations [111, 141, 142]. Consequentially, future work, that is beyond the scope of this thesis, will be needed to investigate this transition (from initial awareness of a bystander via a bystander awareness system to an active collaborator in a cross-reality interaction) to determine which awareness needs persist regardless of the co-presence's role within the interaction (e.g. be they a bystander, co-located VR/AR/MR user, etc), and which are role specific (e.g. only applicable/needed when the co-presence is a bystander, when a co-located AR collaborator, etc).

7.8 Conclusions

Through a lab experiment, Experiment 5, this chapter investigated VR user awareness needs across a variety of bystander-VR user interaction scenarios. This experiment was designed to investigate what influence contextual factors such as the bystander's actions and position relative to the VR user, and the bystander with whom the VR user is interacting had on a VR user's awareness needs during bystander-VR user interactions.

Experiment 5's results provide a strong foundation to develop our understanding of how bystander awareness systems will be used. The results show VR users do not manage awareness needs based solely on the usability of bystander awareness systems. Rather that bystander awareness is managed based on the demands of social context weighted against desired levels of immersion in VR, individual priorities and concerns (e.g. to prioritise physical safety, the social interaction, privacy, etc), and contextual factors (e.g. their relationship to the bystander, the interaction's proxemics, the bystander's actions, etc). To summarise the various VR user attitudes towards how bystander awareness should be increased, four personas for how VR users expect bystander awareness to be provided during bystander-VR user interactions were identified. Additionally, three critical moments within bystander-VR user interactions were derived. 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 a switch in the prioritised awareness modality. Whilst subsequent works will likely refine and expand upon these, they nonetheless show how awareness systems can be used to address fundamentally different awareness problems, that awareness needs contextually change during interactions, and provide a promising method of evaluating the nuance of awareness systems design/usage in future works. The results of Chapter 7 can therefore be used to answer **Research Question 5** as follows:

- **RQ5:** When providing a VR user with increased bystander awareness...
  - **5.1.** what are critical moments when awareness techniques should change?
  - **5.2.** how do awareness needs change at critical moments?

Given the results of Experiment 5, the answer to Research Question 5 is that three critical moments which elicit a significant change in a VR user's awareness technique in use are: (M1) "The Initial Point of Bystander Contact", (M2) "Bystander Entry Into The Play Area", and (M3) "Verbal Bystander-VR User Exchanges".

At these critical moments, VR users' awareness needs were found to dynamically vary based on the demands of the interaction and social context. At M1: "The Initial Point of Bystander Contact", the results show a clear desire for increased visual awareness of the bystander to provide an initial notification of bystander existence, albeit with varying amounts of visual information. At M2: "Bystander Entry Into The Play Area", the results show a clear desire for increased visual bystander awareness using awareness techniques which continuously relay the bystander's position relative to the VR user, to increase safety and reduce the risk of an accidental collision. Finally, at M3: "Verbal Bystander-VR User Exchanges", the results show a clear desire and prioritisation of aural awareness to best fit and accommodate the on-going, aural, needs of the interaction. Such changes in awareness needs demonstrate that no single awareness technique can support the dynamic and changing 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 the bystander, proximity, bystander actions).

Chapter 8

Conclusions

8.1 Introduction

This thesis made the following statement in its introduction:

> *This thesis asserts VR headsets can better support interactions between VR users and bystanders through technology-mediated bystander awareness systems. This thesis presents new insights into how interactions between bystanders and VR users occur, identifying impediments encountered during these interactions. This thesis also presents the design and evaluation of bystander awareness systems to increase a VR user's awareness of, and facilitate an interruption with, a bystander. Finally, this thesis demonstrates that no single awareness technique can adequately support the awareness needs of VR users during an interaction with a bystander. Instead, a VR user's awareness needs are shown to be a complex trade-off between awareness and immersion, individual priorities and concerns in relation to the bystander, and the influence of experiential and contextual factors.*

In the chapters which followed, research was presented which supports this statement, investigating answers to the thesis research questions. Chapter 3 presents two studies which investigated how bystanders interrupt VR users, and their comfort performing these interruptions. Chapter 4 then built on this work by investigating how bystander-VR user interactions occur in-the-wild. Its results provide an overview of the context of how bystander-VR user interactions occur and what impediments are encountered during them, and further justify the need for awareness systems to support VR users during these interactions. Chapters 5 and 6 then investigate the design of bystander awareness systems: to inform a VR user of bystander co-presence (Chapter 5), to facilitate a verbal bystander-VR user exchanges (Chapter

6). Finally, the results of Chapters 3 to 6 are used to inform Chapter 7 which investigated if/how a VR user's awareness needs vary during an interruption/interaction with a bystander. Chapter 7 demonstrates that VR users expect bystander awareness to be dynamic and contextually change during an interaction with a bystander and that no single awareness system can adequately support the awareness needs of VR users. This chapter now summarises this research and revisits each of the research questions, discussing how they were addressed and summarising their answers. It also summarises the main contributions of this research and discusses areas for future work.

8.2 Research Questions

8.2.1 Research Question 1

- **RQ1:** When bystanders interrupt a VR user...
  - **1.1.** how do they enact interruptions?
  - **1.2.** what factors impact comfort and willingness to enact these interruptions?

Chapters 3 and 4 presented Surveys 1 and 2 and Experiment 1 which investigated how bystanders interrupt VR users, and what factors influence their comfort when interrupting and willingness to perform an interruption strategy. The findings of these chapters show bystanders are comfortable interrupting known VR users, irrespective of interruption setting, using verbal interruptions and/or physical contact. The bystander's relationship to the interrupted VR user was identified as the most influential factor on how they interrupt (preferring verbal interruptions when interrupting unknown VR users) and their comfort doing so (being more uncomfortable interrupting unknown VR users). The VR user's application in use was also highlighted as an influence on the interruption approach, with room-scale VR applications being said to deter bystanders from interrupting using physical contact.

8.2.2 Research Question 2

- **RQ2:** When bystanders and VR users interact...
  - **2.1.** what is the context of the interaction?
  - **2.2.** what impediments are encountered when interacting?

Chapter 4 presented Survey 2 which, through a story based survey approach, collected empirical evidence of in-the-wild bystander-VR user interactions. Its results provide an overview of how these interactions occur, finding most can be categorised as either: *Coexisting*, *Demoing* or *Interrupting* interactions. While bystanders and VR users reported being comfortable and not frustrated when interacting, numerous impediments encountered during these interactions were identified which demonstrate the need for bystander awareness systems as a safety system (to mitigate against malicious bystander actions) and as a usability system (to support and facilitate bystander-VR user interactions).

8.2.3 Research Question 3

- **RQ3:** When notifying a VR user of bystander co-presence what is the impact of withholding...
  - **3.1.** identifiable information about the bystander from the VR user?
  - **3.2.** the bystander's position from the VR user?

Chapter 5 presented Experiment 2 which investigated the consequences of withholding information about a bystander's identity and position when notifying a VR user of their co-presence. Its results show that some VR users if they perceive the relayed information about a bystander to insufficiently contextualise their co-presence will exit VR to obtain this desired information. This work demonstrates a limitation with the design of anonymous bystander awareness systems, one that is has been overlooked by prior works in the literature, and further develops our understanding of the design of these systems.

8.2.4 Research Question 4

- **RQ4:** How may in-VR audio be manipulated to facilitate verbal bystander-VR user interactions?

Chapter 6 presented Experiments 3 and 4 which investigated how the audio experienced by a VR user could be manipulated to increase the user's aural awareness. The results of Experiment 3 found that automatically decreasing in-VR audio volume was an effective method of increasing a VR user's awareness of a nearby sound event. Experiment 4 built on this result, and demonstrated that automatically decreasing in-VR audio volume and partially/fully removing in-VR audio elements can effectively facilitate a verbal bystander-VR user interaction. Its results also highlight differences in VR user preferences towards how bystander awareness is increased, finding some VR users prefer to prioritise increased awareness no matter the cost to immersion in VR whereas others attempt to balance increased awareness with preserved immersion.

8.2.5 Research Question 5

- **RQ5:** When providing a VR user with increased bystander awareness...
  - **5.1.** what are critical moments when awareness techniques should change?
  - **5.2.** how do awareness needs change at critical moments?

Chapter 7 drew from the findings of all the prior chapters in this thesis and presented Experiment 5 which evaluated how a VR user's awareness needs might vary during an interaction with a bystander. Its results identified three emergent critical moments during bystander-VR user interactions which elicit a significant change in VR users awareness needs: *(M1) "The Initial Point of Bystander Contact", (M2) "Bystander Entry Into The Play Area"*, and *(M3) "Verbal Bystander-VR User Exchanges"*. Examining how awareness needs change at these critical moments demonstrates that no single awareness technique can adequately support the needs of VR users. Instead, VR users' awareness needs were shown to dynamically vary based on the demands interaction and social context, as they tried to balance a complex trade-off between awareness and immersion, individual priorities and concerns, and the influence of experiential and contextual factors - motivating the development of *socially intelligent bystander awareness systems* capable of providing the *"best fit"* awareness technique to a given bystander-VR user interaction context.

8.3 Contributions

The thesis makes novel contributions which inform the design and use of bystander awareness systems. Its main contributions are: (1) a study of how bystander-VR user interactions occur and impediments encountered during them, (2) investigations into the design of bystander awareness systems, and (3) an investigation into if/how a VR user's awareness needs vary during an interaction with a bystander. This section summarises these contributions.

8.3.1 Interactions Between Bystanders and VR Users

This thesis contributes three studies (Chapters 3 and 4) which investigated how bystander-VR user interruptions and interactions occur. Findings from these studies show that most bystanders are comfortable interrupting known VR users, irrespective of setting, verbally and/or with physical contact. They show that a bystander's relationship to the VR user is the primary influence behind their comfort and choice of approach when interrupting. They also provide an overview of the context of how bystander-VR user interactions occur, finding most can be categorised as either: *Coexisting, Demoing* or *Interrupting* interactions. Finally, the findings of this work outline numerous impediments that are encountered during these interactions including: VR users being scared and/or surprised by a bystander's interruption/co-presence, bystanders failed attempts to initiate verbal interactions with VR users, and some VR users partially or fully transitioning to reality to accommodate their interaction with a bystander.

This work provides researchers and designers with a set of empirically demonstrated impediments experienced during bystander-VR user interactions which bystander awareness systems can be designed to support. This develops our understanding of the interactions that these awareness systems are designed to support which, in turn, enables more informed design decisions to be made. Furthermore, this work documents a set of bystander-VR interaction scenarios that are empirically shown to occur in-the-wild. These interaction scenarios can be used by researchers and designers when evaluating the design of bystander awareness systems to construct evaluations which recreate actual, proven to occur, interactions - improving the validity of their evaluations of bystander awareness systems. Finally, this work demonstrates definitively the necessity of VR headsets to be equipped with bystander awareness systems: as a safety system (to mitigate against malicious acting bystanders) and as a usability system (to support and facilitate VR users interaction with bystanders).

8.3.2 The Design of Bystander Awareness Systems

This thesis contributes three studies (Chapters 5 and 6) which investigated the design of bystander awareness systems to support bystander-VR user interactions by: informing a VR user when bystanders are co-present (Chapter 5), and facilitating a verbal bystander-VR user interaction (Chapter 6). The findings of these works develop our understanding of the design of bystander awareness systems and can be used by researchers and designers to inform designs used within their own work.

The results of Chapter 5 show that some VR users will exit VR if a notification of co-presence does not provide sufficient information to contextualise the bystander. This behaviour was found to occur for both a lack of identifiable and spatial information about a bystander. This finding highlights a limitation with many works in the literature which have proposed the use of anonymous awareness systems with varying degrees of positional information about the bystander, and develops our understanding of overarching the design of bystander awareness systems to notify a VR user of bystander existence.

The result of Chapter 6, for the first time, outlines multiple methods of manipulating a VR user's experienced audio to effectively facilitate a verbal interaction with a bystander. The findings of Chapter 6 also demonstrate the need to develop bystander awareness systems to support interactions with a bystander more generally. While most works in the literature focus on the problem of informing a VR user when a bystander is co-present, Chapter 6 shows that bystander awareness systems can be built to effectively address other impediments on a VR user's interaction with a bystander, and that VR users want VR headsets to be equipped with awareness systems to address these problems also.

8.3.3 VR User's Dynamic Awareness Needs

This thesis investigated if/how VR user awareness needs vary during an interaction with a bystander (Chapter 7, Experiment 5). The findings of Experiment 5 demonstrate VR users awareness needs are dynamic and that a VR user's bystander awareness must vary during an interaction. The findings show that no single awareness system can adequately support the awareness needs of VR users who balance a complex trade-off between awareness and immersion, individual priorities and concerns, and the influence of experiential and contextual factors. These dynamic awareness needs motivate the development of *socially intelligent bystander awareness systems* in future works, which are envision to be the next significant step towards developing systems that fully support/facilitate cross reality bystander-VR user interactions.

The findings of Experiment 5 also demonstrate shortcomings with the existing evaluation methodologies of bystander awareness systems. Experiment 5's results show how the methodologies widely used in the literature do not consider how disparate approaches towards increasing bystander awareness might be used together. Instead, by focusing on validating an awareness system's effectiveness for increasing awareness and impact on presence, existing evaluation methodologies may produce misleading inaccurate recommendations. To this end, this thesis presents one possible alternative methodology, based on considering the use of awareness systems during critical moments in bystander-VR user interactions, to increase the ecological validity of researchers and designers evaluation of bystander awareness systems in future work.

8.4 Limitations and Future Work

This section will summarise some general limitations of the research as a whole, alongside a discussion of future work that could both address these limitations and further explore the themes brought up in this thesis.

8.4.1 Realising Bystander Awareness Systems in VR Devices

It is worth discussing how the ideas presented within this thesis for *socially intelligent bystander awareness systems* might be realised, technologically, within consumer VR hardware. This thesis often used a Wizard of Oz approach to investigate bystander awareness systems (Experiments 3, 4, and 5), as is common in the literature (e.g. [9, 20, 19, 24]), but it should be highlighted that works have built prototypes capable of detecting a bystander's existence and augmenting a photoreal avatar of them into a VR user's virtual environment [6, 21]. And while the inclusion of such systems within consumer VR hardware will require an advancement in their sensing capabilities, the rapid technical advances seen in these devices in recent years highlights that functionally VR hardware will, in the near future, be capable of understanding the contextual and social information (and more) [78] necessary to realise the inclusion of *socially intelligent bystander awareness systems*.

Advances towards this, and a clear desire from hardware manufacturers to incorporate bystander awareness into VR hardware, can already be seen through Meta's experimental *Space Sense* [17] system included in their Quest [32] headsets. Marketed as a method of increasing awareness of bystanders within a VR user's play area, such a system could be considered the first dedicated, albeit somewhat basic, bystander awareness system within a consumer VR device. One can imagine in the near future, when the technology has advanced further, that a range of different awareness systems might be included with users able to configure their device to trigger preferred awareness techniques at different social and interaction contexts (e.g. critical moments known to elicit changes in awareness needs). Such a device might then, for example, utilise human action recognition [177] or social signal processing techniques [146, 78] to recognise and act on social signals and behaviours of bystander and/or VR user to provide the user with their preferred awareness technique relative to any experienced on-going interaction with a bystander.

Going forward it is essential the design of bystander awareness systems benefit from the technical advances made in VR hardware. Advances in the processing and sensing capabilities will enable the use of techniques such as social signal processing [146] or human action recognition [177] to create systems capable of recognising and acting on social signals and behaviours of bystander and/or VR users. But future work is needed to utilise such techniques to develop *socially intelligent bystander awareness systems* capable of assigning awareness priorities as the demands of the interaction require. Future work is also needed to further develop visual sensing techniques such as depth maps [6], point cloud [109], etc, to enable, as resource efficiently as possible, selective augmentation of photoreal bystander avatars into a VR user's virtual environment [6] and other designs of bystander awareness systems. Therefore, while, technologically, VR devices might in the near future be capable of being equipped with *socially intelligent bystander awareness systems* there remains open technical challenges which must first be addressed before their inclusion in such a future VR device will be enabled.

8.4.2 Alternative Bystander-VR User Interaction Contexts

The type of bystander-VR user interaction used in the experiments of this thesis was fixed, and investigated: (a) interactions with a single, known bystander, (b) interactions occurring in private settings, (c) a user using VR for entertainment purposes.

This interaction type was used to best recreate the affordances of typical home VR usage [33, 31, 36]. However, prior work by Geroge et al. has shown that the context of a bystander-VR user interaction (e.g. the application being used by the VR user) can influence a VR user's response to an awareness system [10]. Furthermore, the findings of Chapters 3, 4, and 7 of this thesis demonstrate the influence of different bystander-VR user interactions types (e.g. an interaction with an unknown VR user) can influence the behaviours of both bystanders and VR users during them.

Future work should therefore investigate the design and use of bystander awareness in alternative usage contexts than were explored in this thesis. For example, a VR user in a workplace setting performing a productivity task may have significantly different awareness needs than a user at home using VR for entertainment. While one would expect there to be some crossover in awareness needs, as bystander awareness as a safety feature remains in all contexts (Chapters 4, 5, and 7), differences may also exist (e.g. a VR user wanting lower levels of awareness when focusing on a productivity task compared to gaming in VR).

8.4.3 The Design of Bystander Awareness Systems

This thesis made several contributions which develop our understanding of the design of bystander awareness systems. However, open questions remain regarding the design of these awareness systems. For example, in the experiments of this thesis any visual approach being evaluated was designed to *"fit correctly"* within the presented VR scene and was not clipping through any objects, out of proportion relative to the rest of the scene, etc [72]. While ensuring any visual systems fit within a virtual environment is a widely used approach in the literature (e.g.[6, 21, 52, 22, 24]), it is likely VR users will use applications where a *"universal bystander awareness system"* does not *"fit correctly"* within the VR scene. Yet, at present, it is unknown what impact this has on a VR user's response to an awareness system. Therefore, future work could look to investigate this, and how to best accommodate any impact (e.g. should awareness systems be configurable on a per application basis).

Open questions remain also regarding how the design of awareness systems scale to support multiple bystanders at once. While this thesis, and all prior works in the literature, have focused on interactions involving one VR user and one bystander, bystander-VR user interactions often involved multiple bystanders [7]. Future work could therefore also investigate the scalability of the bystander awareness systems presented in this thesis and the literature to evaluate which approaches are effective and ineffective for supporting multiple bystanders at once.

8.4.4 In-Situ Research

This thesis focused on surveys and lab-based experiments, but a logical trajectory for this research would be studying the use of bystander awareness systems in the environments they are intended to be used. For example, Experiment 5 investigated the use of awareness systems through a lab experiment based on interaction scenarios captured by Survey 2. While this provided a structured method of evaluating awareness needs across a range of interactions it does not perfectly replicate in-the-wild behaviours and does not allow for emergent behaviours to occur. Future work should therefore evaluate bystander awareness systems in-situ in the actual settings and contexts in which they will be used long term. While lab-based methodologies such as acting out bystander interactions [10] or nesting simulated realities [49, 172] may provide valid alternative approaches, in-situ evaluations are more ecologically valid, allow a wider range of interactions to be experienced, and for emergent, unplanned interactions to naturally occur.

In-situ evaluations of awareness systems will also enable investigation into the longitudinal impact and use of these awareness systems. For example, currently it is unknown if VR users will adjust their awareness preferences over time, e.g. a VR user might initially believe it is essential bystanders are represented as photoreal avatars during their entire interaction with them but over time decide only to display a photoreal avatar when they are inside the VR user's play area. This longitudinal understanding of awareness systems usage is becoming increasingly important as bystander awareness systems are incorporated into consumer VR headsets [16, 17] and future work should look to fill this gap in our understanding of these systems.

8.4.5 Background and Culture of Participants

The majority of the participants that took part in the experiments of this thesis were University of Glasgow students. Although there was a mixture of nationalities, a large portion were from Europe. These participants bring particular social customs from their respective backgrounds, which limits the results of this thesis, to a degree, due different social customs and expectations existing within cultures globally [178], which have been shown to influence how individuals use [179, 180] and interact with [181, 182] a system. For example, an individual with a Western European background may have a different set of awareness needs or use awareness systems differently than an individual with an Middle Eastern background due to differing expectations for social interactions between individuals should occur (e.g. an individual from one cultural background might remain in VR upon being notified of a bystander's existence whereas another might exit VR immediately not to be perceived as being impolite).

Future work should therefore look to understand how such cultural differences might influence how bystander-VR user interactions occur, and differences in how bystander awareness systems are designed and used. This could be achieved through studies designed to investigate what differences might exist directly, or by replicating the research presented in this thesis and comparing the results obtained. For example, while the surveys studies presented in this thesis were advertised as widely as possible (e.g. through mailing lists, social media, and a variety of different online platforms) to achieve greater ecological validity, respondents were limited to participating in English. This, to a degree, limits the data captured and future work could replicate Survey 1 and 2 in other languages, targeting cultures where differences are expected to emerge, then compare the results to those presented within this thesis.

8.5 Conclusions

Bystander-VR user interactions occur frequently and are often problematic. This thesis investigated these interactions, and contributes an empirical overview of how they occur and what impediments are encountered during them. This thesis also investigated the design of technology-mediated bystander awareness systems to support these interactions. It makes contributions which improve the effectiveness of systems designed: to inform a VR user when bystanders are co-present, and to facilitate verbal bystander-VR user exchanges. Finally, this thesis investigated if/how a VR user's awareness needs vary during an interaction with a bystander, demonstrating that VR users want bystander awareness to be dynamic and contextually change relative to the demands of an on-going interaction. This research allows designers to better understand bystander-VR user interactions and the design and use of awareness systems to support them.

Appendix A

Appendix A: Survey 1 PDF

A pdf of the survey used to conduct Survey 1 in Chapter 3 is included on the pages that follow.

Virtual Reality Headset User Interaction Survey (copy)

Page 1: Information Page

Thank you for participating in this survey about virtual reality (VR) headsets and how someone might attempt to get the attention of someone using one in a variety of contexts.

If you have any questions about this research, please contact:

Joseph O'Hagan

University of Glasgow

j.ohagan.1@research.gla.ac.uk

What is the purpose of this study?

The purpose of this study is to understand how you would expect to get the attention of someone wearing a virtual reality (VR) headset in a variety of contexts. The survey will ask how you would prefer to initiate a communication with a virtual reality headset user in a variety of contexts. It will also ask for your level of comfort in doing this.

What is the structure of this survey?

You will be presented with an image showing a real world context and brief description of the situation. You will then be asked to pick a preferred method of getting the VR headset user’s attention and your level of comfort doing so.

There are 4 contexts in total to complete in this survey. It will take approximately 5 minutes to complete.

What are the possible benefits of participating?

This survey will help us to design methods for attracting the attention of VR headset users. Your response will be used to develop prototype methods which may be eventually used in commercial VR headsets.

What happens at the end of this study?

The results of this study may be used in research publications. The results may also be presented at scientific meetings or in talks at academic institutions. Results will always be presented in such a way that data from individual volunteers cannot be identified.

Can I withdraw from the study?

Yes, your participation in this research project is voluntary, and you may withdraw from the research at any time and for any reason, without explaining why.

Can I ask questions about the research project?

Yes, you may ask more questions about the study at any time - before, during and after the study. Use the contact information provided above if you have any questions

(1) Please confirm your participation in this study by completing this consent form (please select all). ✱ *Required*

Please select at least 5 answer(s).

- ☐ I confirm that I have read and understood the participant information sheet for the above study and have had the opportunity to ask questions
- ☐ I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason
- ☐ I understand that the data collected may be used in publications, presentations or on websites where this research will be disseminated
- ☐ I agree that the anonymised data can be made publicly available after this research is complete
- ☐ I am over 16 years old

Page 2: Demographic Questions

How old are you?

What is your gender?

- Male
- Female
- Other
- Prefer not to say

How much prior experience do you with virtual reality headsets?

- 1 (None)
- 2 (A little)
- 3 (Some)
- 4 (Much)
- 5 (A lot)

Page 3: Situation 1 (of 4): Private Spaces

Situation 1 (of 4): Private Spaces

Please consider the picture above.

Consider the scenario where you want to attract the attention of a VR headset user while in a private setting (e.g. your home).

If the person was your friend:

How comfortable would you be getting their attention?

- Very Uncomfortable
- Uncomfortable
- Neutral
- Comfortable
- Very Comfortable

How would you be willing to get their attention? (Please select at least 1)

Please select at least 1 answer(s).

- ☐ Touch: e.g. “Make physical contact with them”
- ☐ Speech: e.g. “Speak to them”
- ☐ Gestures: e.g. “Wave or gesture at them”
- ☐ Purpose Built Peripherals: e.g. “Use a purpose built peripheral for attracting their attention”
- ☐ Keyboard: e.g. “Press a key on a nearby keyboard”
- ☐ Other (any other interruption strategy, please specify below)

Please specify:

If the person was a stranger:

How comfortable would you be getting their attention?

- ○ Very Uncomfortable
- ○ Uncomfortable
- ○ Neutral
- ○ Comfortable
- ○ Very Comfortable

How would you be willing to get their attention? (Please select at least 1)

Please select at least 1 answer(s).

- ☐ Touch: e.g. “Make physical contact with them”
- ☐ Speech: e.g. “Speak to them”
- ☐ Gestures: e.g. “Wave or gesture at them”

☐ Purpose Built Peripherals: e.g. “Use a purpose built peripheral for attracting their attention”

☐ Keyboard: e.g. “Press a key on a nearby keyboard”

☐ Other (any other interruption strategy, please specify below)

Please specify:

Page 4: Situation 2 (of 4): Public Spaces

Situation 2 (of 4): Public Spaces

Please consider the picture above.

Consider the scenario where you want to attract the attention of a VR headset user while in a public space (e.g. a cafe, a museum, etc).

If the person was your friend:

How comfortable would you be getting their attention?

- Very Uncomfortable
- Uncomfortable
- Neutral
- Comfortable
- Very Comfortable

How would you be willing to get their attention? (Please select at least 1)

Please select at least 1 answer(s).

☐ Touch: e.g. “Make physical contact with them”

☐ Speech: e.g. “Speak to them”

☐ Gestures: e.g. “Wave or gesture at them”

☐ Purpose Built Peripherals: e.g. “Use a purpose built peripheral for attracting their attention”

☐ Keyboard: e.g. “Press a key on a nearby keyboard”

☐ Other (any other interruption strategy, please specify below)

Please specify:

____

If the person was a stranger:

How comfortable would you be getting their attention?

○ Very Uncomfortable

○ Uncomfortable

○ Neutral

○ Comfortable

○ Very Comfortable

How would you be willing to get their attention? (Please select at least 1)

Please select at least 1 answer(s).

☐ Touch: e.g. “Make physical contact with them”

☐ Speech: e.g. “Speak to them”

☐ Gestures: e.g. “Wave or gesture at them”

☐ Purpose Built Peripherals: e.g. “Use a purpose built peripheral for attracting their attention”

- [ ] Keyboard: e.g. “Press a key on a nearby keyboard”
- [ ] Other (any other interruption strategy, please specify below)

Please specify:

Page 5: Situation 3 (of 4): Private Transport

Situation 3 (of 4): Private Transport

Please consider the picture above.

Consider the scenario where you want to attract the attention of a VR headset user while in private transport (e.g. sitting as a passenger next to a VR user in a car).

If the person was your friend:

How comfortable would you be getting their attention?

- Very Uncomfortable
- Uncomfortable
- Neutral
- Comfortable
- Very Comfortable

How would you be willing to get their attention? (Please select at least 1)

Please select at least 1 answer(s).

- [ ] Touch: e.g. “Make physical contact with them”
- [ ] Speech: e.g. “Speak to them”
- [ ] Gestures: e.g. “Wave or gesture at them”
- [ ] Purpose Built Peripherals: e.g. “Use a purpose built peripheral for attracting their attention”
- [ ] Keyboard: e.g. “Press a key on a nearby keyboard”
- [ ] Other (any other interruption strategy, please specify below)

Please specify:

If the person was a stranger:

How comfortable would you be getting their attention?

- ○ Very Uncomfortable
- ○ Uncomfortable
- ○ Neutral
- ○ Comfortable
- ○ Very Comfortable

How would you be willing to get their attention? (Please select at least 1)

Please select at least 1 answer(s).

- [ ] Touch: e.g. “Make physical contact with them”
- [ ] Speech: e.g. “Speak to them”
- [ ] Gestures: e.g. “Wave or gesture at them”
- [ ] Purpose Built Peripherals: e.g. “Use a purpose built peripheral for attracting their

attention”

- ☐ Keyboard: e.g. “Press a key on a nearby keyboard”
- ☐ Other (any other interruption strategy, please specify below)

Please specify:

Page 6: Situation 4 (of 4): Public Transport

Situation 4 (of 4): Public Transport

Please consider the picture above.

Consider the scenario where you want to attract the attention of a VR headset user while in public transport (e.g. while sat next to them as a passenger on a plane or train).

If the person was your friend:

How comfortable would you be getting their attention?

- ○ Very Uncomfortable
- ○ Uncomfortable
- ○ Neutral
- ○ Comfortable
- ○ Very Comfortable

How would you be willing to get their attention? (Please select at least 1)

Please select at least 1 answer(s).

- ☐ Touch: e.g. “Make physical contact with them”
- ☐ Speech: e.g. “Speak to them”
- ☐ Gestures: e.g. “Wave or gesture at them”
- ☐ Purpose Built Peripherals: e.g. “Use a purpose built peripheral for attracting their attention”
- ☐ Keyboard: e.g. “Press a key on a nearby keyboard”
- ☐ Other (any other interruption strategy, please specify below)

Please specify:

If the person was a stranger:

How comfortable would you be getting their attention?

- ○ Very Uncomfortable
- ○ Uncomfortable
- ○ Neutral
- ○ Comfortable
- ○ Very Comfortable

How would you be willing to get their attention? (Please select at least 1)

Please select at least 1 answer(s).

- ☐ Touch: e.g. “Make physical contact with them”
- ☐ Speech: e.g. “Speak to them”
- ☐ Gestures: e.g. “Wave or gesture at them”

- [ ] Purpose Built Peripherals: e.g. “Use a purpose built peripheral for attracting their attention”
- [ ] Keyboard: e.g. “Press a key on a nearby keyboard”
- [ ] Other (any other interruption strategy, please specify below)

Please specify:

Page 7: Closing Page

Thank you for participating in this survey about virtual reality (VR) headsets and how someone might attempt to get the attention of someone using one in a variety of contexts.

If you have any questions about this research, please contact:

Joseph O'Hagan

University of Glasgow

j.ohagan.1@research.gla.ac.uk

Appendix B

Appendix B: Survey 2 PDF

A pdf of the survey used to conduct Survey 2 in Chapter 4 is included on the pages that follow.

Interactions With VR Users (v6)

Page 1

This survey investigates interactions between VR users and nearby bystanders.

If you have any questions about this research, please contact:

- Joseph O'Hagan
- j.ohagan.1@research.gla.ac.uk

What are the possible benefits of participating?

- This survey will assist in the understanding of virtual reality and be may used to develop iterations on the existing designs which may be used in future VR headsets.

What happens at the end of this study?

- The results of this study may be used in research publications. The results may also be presented at scientific meetings or in talks at academic institutions. Results will always be presented in such a way that data from individual volunteers cannot be identified.

Can I withdraw from the study?

- Yes, your participation in this research project is voluntary, and you may withdraw from the research at any time and for any reason, without explaining why. Please use the contact information provided to do this if desired.

Can I ask questions about the research project?

- Yes, you may ask more questions about the study at any time - before, during and after the study. Use the contact information provided above if you have any questions

Is there a reward for my participation?

- As an optional reward for participation, participants who complete the entire questionniare (only eligible if participants complete the story data portion of the questionnaire) can take part in a loterry for one of two £20 Amazon vouchers. Winners of the lottery will be notified by email after the questionnaire is complete.

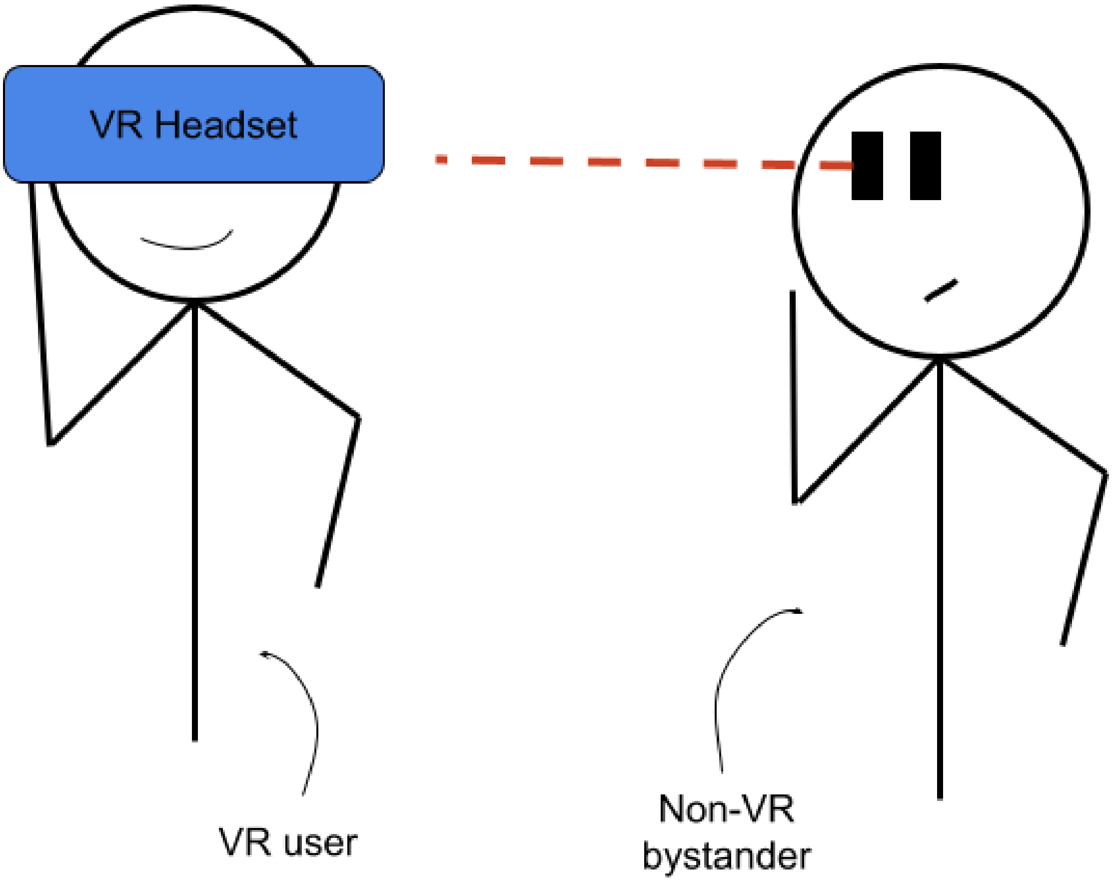
Please confirm your participation in this study by completing this consent form (please select all)

- ☐ I confirm that I have read and understood the participant information and have had the opportunity to ask questions
- ☐ I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason
- ☐ I understand that the data collected may be used in publications, presentations or on websites where this research will be disseminated
- ☐ I agree that the anonymised data can be made publicly available after this research is completed
- ☐ I am over 16 years old

Story Capture

With the rise in popularity of VR headsets, interactions between VR users and non-VR bystanders are becoming more frequent. However, little is currently known about how VR users and nearby people interact with one another.

The goal of this section is to capture stories of real experiences you have had as a VR user or bystander when interacting with the other.



Have you experienced or observed a real situation similar to this?

- Yes, I was the VR user
- Yes, I was the non-VR bystander
- Yes, as both the VR user and non-VR bystander
- Yes, I was neither but I observed such a situation (I was a third party)

- No

How often have you experienced a real situation like this?

- Never
- A little
- Occasionally
- Often
- A lot

To what extent do you typically feel frustrated during VR user and non-VR bystander interactions?

- Not Applicable
- Not at all
- Slightly frustrated
- Somewhat frustrated
- Frustrated
- Very frustrated

How often have you felt the need to interact with a VR user?

- Not Applicable
- Never
- A little
- Occasionally
- Often

○ All the time

Story Capture (1)

You indicated you have experienced or observed a real situation similar to the one described on the previous page. Please describe the interaction between the VR-user and the non-VR bystander as accurately as possible.

Does the situation you described involve physical contact or verbal communication between the VR user and the non-VR bystander?

- It involved physical contact AND verbal communication
- It involved physical contact only
- It involved verbal communication only
- It involved neither

Because you selected "It involved neither" please describe a situation where interaction between the VR-user and the non-VR bystander involved physical contact and/or verbal communication. Please describe it as accurately as possible.

Story Capture (2a)

Please give us more details about the situation you described on the prior page (if you know them)

What did the VR user / non-VR bystander do?

How did the VR user / non-VR bystander react?

Where did the situation take place (e.g. in a home, in an office at work, etc)

Did the VR user / non-VR bystander know each other?

- Yes
- No
- Not sure

Were you the VR user, the non-VR bystander, someone else?

- I was the VR user
- I was the non-VR bystander
- I was neither but I observed such a situation (I was a third party)

Because you have reached this portion of the survey you are elligible for entry into a lottery to win one of two £20 Amazon vouchers. Only submissions associated with genuine data (after experimenter inspection) will be entered into the prize draw. Winners of the lottery will be notified by email once the survey has completed running. If you would like to take part in the lottery please indicate below

- No, I do not want to take part
- Yes, I would like to take part

Please enter your email address. ***IMPORTANT: Your email address will be used for the lottery only and then deleted.***

Story Capture (2b)

Please give us more details about the situation you described on the prior page (if you know them). As you described 2 situations please use the ***last situation*** you described.

What did the VR user / non-VR bystander do?

How did the VR user / non-VR bystander react?

Where did the situation take place (e.g. in a home, in an office at work, etc)

Did the VR user / non-VR bystander know each other?

- Yes
- No
- Not sure

Were you the VR user, the non-VR bystander, someone else?

- I was the VR user
- I was the non-VR bystander
- I was neither but I observed such a situation (I was a third party)

Because you have reached this portion of the survey you are elligible for entry into a lottery to win one of two £20 Amazon vouchers. Only submissions associated with genuine data (after experimenter inspection) will be entered into the prize draw. Winners of the lottery will be notified by email once the survey has completed running. If you would like to take part in the lottery please indicate below

- No, I do not want to take part
- Yes, I would like to take part

Please enter your email address. ***IMPORTANT: Your email address will be used for the lottery only and then deleted.***

The Bystander Perspective

This final section investigates what information you, as the non-VR bystander, wish to have of a nearby VR user and your feelings towards a potential interaction with them.

How comfortable are you getting a VR user's attention?

- Very Uncomfortable
- Uncomfortable
- Neutral
- Comfortable
- Very Comfortable

How comfortable are you avoiding a VR user (e.g. doing a task in the same room as them)?

- Very Uncomfortable
- Uncomfortable
- Neutral
- Comfortable
- Very Comfortable

How comfortable are you navigating past / around a VR user (e.g. moving past or near them)?

- Very Uncomfortable
- Uncomfortable
- Neutral

- Comfortable
- Very Comfortable

To what extent do you feel isolated from those playing VR?

- Not at all isolated
- Slightly isolated
- Somewhat isolated
- Very isolated
- Extremely isolated

Does lack of eye contact with a VR user bother you (e.g. when you speak to them / are around them)?

- Never
- Infrequently
- Sometimes
- Often
- All the time

Does the occluded view of a VR user's face bother you (e.g. when you speak to them / are around them)?

- Never
- Infrequently
- Sometimes
- Often

○ All the time

Do you have any comments or feedback relating to comfort when interacting with a VR user?

As a bystander, what sort of information would you want to know about a nearby VR user?

☐ Visual Content (e.g. what the VR user sees)

☐ Auditory Content (e.g. what the VR user hears)

☐ Awareness of Reality (e.g. do they know you are there)

☐ Content Type (e.g. what the VR user is doing - "playing a game", "using VR for work", etc)

☐ Interruptibility (e.g. do they want to be disturbed)

☐ Time in VR (e.g. how long they have been in VR for)

☐ Other

If you selected Other, please specify:

Demographic Data

How old are you?

[ ]

What is your gender?

- ☐ Female
- ☐ Male
- ☐ Prefer not to say
- ☐ Other

If you selected Other, please specify:

[ ]

How much prior experience with VR headsets do you have?

- ○ None
- ○ A little
- ○ Some
- ○ Much
- ○ A lot

Final page

Thank you for participating in this survey.

If you have any questions about this research, please contact:

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If you would like to report additional situations where you experienced or observed a real world interaction between a VR user and non-VR bystander then please use the following link:

https://glasgow-research.onlinesurveys.ac.uk/interactions-with-vr-users-v5-story-only-submission

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