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How VR Personal Space Invasion Countermeasures Impact the Invader

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Abstract

Social virtual reality (VR) enables users to interact within immersive shared environments, making interpersonal interaction central to the user experience. As these platforms continue to mature, regulating personal space has become an important design challenge: personal space invasions (PSIs) can be unintended, yet still disruptive for the users involved. Existing research has primarily examined how to protect users whose personal space is violated, while paying comparatively little attention to how countermeasures affect the approaching user. To address this gap, this thesis investigates personal space countermeasures through two complementary user studies. The first, a controlled VR experiment with 24 participants, evaluated three countermeasures using subjective questionnaires, ranking tasks, and physiological measurements. The second, a qualitative study with 12 participants, examined interactions from both users' perspectives through semi-structured interviews and was analysed using thematic analysis. Across both studies, participants preferred countermeasures that communicated personal space boundaries before restricting movement. They perceived gradual interventions as more understandable, fair, and socially acceptable than forceful approaches, and they emphasised the need to adapt countermeasures to contextual factors such as interpersonal relationships, environmental conditions, and perceived intent. These findings indicate that effective personal space regulation in social VR should consider both interaction partners rather than focusing only on the user whose personal space is violated. This thesis contributes design principles for reciprocal, context-aware personal space regulation that prioritises communication before enforcement and supports the continued maturation of social VR. These findings have direct implications for developers of social VR platforms seeking to design personal space mechanisms that balance user safety with social autonomy for all parties involved in an interaction.

Überblick

Soziale virtuelle Realität (VR) ermöglicht Nutzer*innen die Interaktion in immersiven gemeinsamen Umgebungen und macht zwischenmenschliche Interaktionen zu einem zentralen Bestandteil des Nutzungserlebnisses. Mit der zunehmenden Weiterentwicklung dieser Plattformen ist die Regulierung des persönlichen Raums zu einer wichtigen Gestaltungsherausforderung geworden, da Verletzungen des persönlichen Raums (PSIs) unbeabsichtigt sein können und dennoch die beteiligten Personen beeinträchtigen. Die bisherige Forschung konzentrierte sich vor allem auf den Schutz der betroffenen Person, während die Auswirkungen von Gegenmaßnahmen auf die sich nähernde Person bislang kaum untersucht wurden. Um diese Forschungslücke zu schließen, untersucht diese Arbeit Gegenmaßnahmen zur Regulierung des persönlichen Raums anhand zweier komplementärer Nutzerstudien. Eine kontrollierte VR-Studie mit 24 Teilnehmenden evaluierte drei Gegenmaßnahmen mithilfe von Fragebögen, Rangordnungsaufgaben und physiologischen Messungen. Eine zweite qualitative Studie mit 12 Teilnehmenden untersuchte Interaktionen aus beiden Perspektiven anhand semistrukturierter Interviews, die thematisch ausgewertet wurden. Über beide Studien hinweg bevorzugten die Teilnehmenden Gegenmaßnahmen, die persönliche Distanzgrenzen kommunizierten, bevor sie Bewegungen einschränkten. Schrittweise Interventionen wurden als verständlicher, fairer und sozial akzeptabler wahrgenommen als unmittelbare Eingriffe. Zudem betonten die Teilnehmenden die Notwendigkeit, Gegenmaßnahmen an zwischenmenschliche Beziehungen, die Umgebung und wahrgenommene Absichten anzupassen. Die Ergebnisse zeigen, dass eine wirksame Regulierung des persönlichen Raums in sozialer VR beide Interaktionspartner*innen berücksichtigen sollte, anstatt sich ausschließlich auf den Schutz der betroffenen Person zu konzentrieren. Die Arbeit leitet daraus Gestaltungsprinzipien für eine reziproke und kontextabhängige Regulierung des persönlichen Raums ab, die Kommunikation vor unmittelbarer Durchsetzung priorisiert und so zur Weiterentwicklung sozialer VR beiträgt. Die Ergebnisse liefern zudem praktische Implikationen für die Gestaltung von Mechanismen zur Regulierung des persönlichen Raums, die Sicherheit und soziale Autonomie aller an einer Interaktion Beteiligten in Einklang bringen.

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Conventions

Throughout this thesis, we use the following conventions:

- The thesis is written in British English.
- The first person is written in plural form.

Definitions are set off in coloured boxes.

EXCURSUS:
Excursuses are set off in orange boxes.

Where appropriate, paragraphs are summarised by one or two sentences that are positioned at the margin of the page.

This is a summary of a paragraph.

Conditions are represented in small-caps text, whereas questionnaire categories are represented in typewriter-style text, and the individual questionnaire items within each category are presented in italics.

CONDITION
`Category`
Item

Graphics used for data visualisation are generated using Python scripts and are designed to ensure accessibility through a colour-blind-friendly format.

To improve readability throughout the thesis, the sources of all external images are compiled in Appendix A rather than listed in the individual chapters.

Chapter 1

Introduction

"The screen is a window through which one sees a virtual world. The challenge is to make that world look real, act real, sound real, feel real."

—Ivan E. Sutherland (1965)

From the advent of the Sword of Damocles, introduced by Sutherland [1968], to contemporary consumer-grade *head-mounted displays* (HMDs), *virtual reality* (VR) has undergone rapid technological advancement. Initially, VR was confined to a limited range of domains, including military [Furness, 1986] and aerospace institutions [Fisher et al., 1988]. During the 2010s, however, cost-effective and high-performance VR devices, including the Oculus Rift and HTC Vive, widened access for researchers and enthusiasts, expanding opportunities for innovation within the field [Shang and Alena, 2025]. By 2023, more than 171 million individuals were using VR technology worldwide[1], while the market was valued at approximately USD 15.6 billion and projected to exceed USD 40 billion by 2031[2]. These figures reflect VR's trajectory from a novelty-driven technology towards wider adoption.

VR evolved from early systems to modern HMDs

Increasing number of VR users

[1] `https://drawandcode.com/learning-zone/how-many-people-use-virtual-reality/` [Accessed: April 2026]

[2] `https://www.mordorintelligence.com/industry-reports/virtual-reality-market` [Accessed: April 2026]

Rise of social VR as a research focus

As VR has matured, it has opened new research directions across multiple domains, notably at the intersection of *human–computer interaction* (HCI), psychology, and the social applications of VR. Within these environments, the growing user base has intensified attention to user well-being [Schaffer et al., 2026]. This combined academic and industry interest has made social VR a central focus within contemporary VR research [Han and Bailenson, 2024], motivating further investigation into its design, interaction paradigms, and associated challenges.

1.1 Social Virtual Reality

The focus is social VR within social XR

Before examining the research context in detail, it is useful to clarify the technological landscape surrounding social VR, as the broader category of *extended reality* (XR), an umbrella term for augmented, virtual, and mixed reality technologies that enable users to connect and interact with one another [Niamut, 2021]. This provides the conceptual frame for this thesis's focus on VR, as social XR encompasses the broader ecosystem of immersive social technologies; however, this thesis focuses specifically on social VR.

Definition: *Social Virtual Reality*

SOCIAL VIRTUAL REALITY:
"Social virtual reality (VR) represents a growing set of multiuser applications that enable people to interact with one another in virtual space through VR head-mounted displays (HMDs)." [McVeigh-Schultz et al., 2019]

Social VR research spans many areas, increasingly focusing on harassment

Recent social VR research spans areas such as communication practices [Cho and Riecke, 2025; Gunkel et al., 2021], interaction design [Yassien and Abdennadher, 2025; Zhou et al., 2026], users' emotional experiences [Kuang et al., 2026; Yoon et al., 2026], and privacy and ethics [Chang et al., 2025]. Within this field, harassment has become a critical area of concern, as it can induce psychological distress and contribute to the long-term exclusion of

marginalised groups when affected users disengage from these platforms [Zhang et al., 2023].

Social VR harassment spans verbal, sexual, identity-based, and personal space invasion

Harassment in social VR manifests in diverse forms, including verbal abuse, sexual harassment, and identity-based harassment [Gerritse et al., 2026]. Personal space invasion differs from many other forms of harassment because its perception and impact are highly context-dependent: users' responses may vary depending on factors such as locomotion techniques [Connolly et al., 2025], cultural background [Hasler and Friedman, 2012], and gender differences [Nassiri et al., 2004].

Proxemics research dates to the 1960s

Although social VR is relatively new, proxemics, introduced by Hall [1966], and the related concept of personal space invasion, as examined by Felipe and Sommer [1966], are grounded in longstanding research on human spatial behaviour. This research developed alongside early advances in VR and has become extensive within psychology, encompassing studies across cultural contexts [Aiello and Thompson, 1980; Baldassare and Feller, 2009], age groups [Dean et al., 1976; Mirlisenna et al., 2024], and gender [Fisher and Byrne, 1975; Skolnick et al., 1977]; together, these factors define one's perceptions of personal space.

HCI informs countermeasures against personal space violations in social VR

Within this context, HCI provides a foundation for addressing these personal space violations in social VR: it informs the design of interaction techniques and system-level countermeasures that can mitigate unwanted proximity. Personal space bubbles in VR platforms such as Meta Horizon Worlds and Rec Room illustrate one such approach [Zhu and Parker, 2025]. Another example is the "talk-to-the-hand" gesture implemented in Rec Room, which allows users to mute and ignore disruptive participants [McVeigh-Schultz et al., 2019]. Blehm [2025] extends this work by evaluating three distinct countermeasures from the recipients' perspective and examining their perceived usability and effectiveness in social VR environments.

Invader's perspective remains overlooked, highlighting a key research gap

Although research has increasingly examined personal space invasion and its countermeasures in social VR from the recipients' perspective, the approaching user's, or invader's, perspective remains comparatively underexplored. This gap raises an important question regarding how current countermeasures influence approaching users and how support mechanisms can be designed to effectively prevent violations while promoting the well-being of all individuals involved. To address this gap, the present work first investigates how invaders respond to existing countermeasures before considering how these insights can inform more mutually acceptable support mechanisms. It is hence guided by the following research questions:

RQ1 How do invaders respond to countermeasures, and which types of countermeasures do they perceive as most acceptable or preferable?

RQ2 What countermeasures or support mechanisms can be designed to reduce unintentional PSI while remaining mutually acceptable?

Two-study approach: controlled experiment and qualitative interview study

Extending Blehm's work, this thesis uses two complementary studies to investigate personal space invasion from the invader's perspective. Study 1 examines the invader's perspective in a controlled experimental setting, in which participants evaluate three countermeasures. Study 2 uses a retrospective reflection followed by semi-structured interviews: participants assess the same set of conditions as in the first study while reflecting on and comparing the invader's and recipient's perspectives.

Aim of the thesis

Together, these investigations examine personal space invasion in social VR from the invader's perspective and consider how users perceive countermeasures across interaction roles. The thesis aims to clarify how invaders respond to countermeasures and derive design implications for invader-aware support mechanisms that reduce unintentional violations while promoting user well-being.

1.2 Outline

This thesis is organised into six chapters. After this introductory chapter, Chapter 2 reviews existing literature on social VR, proxemics, PSI, and personal space countermeasures. Chapter 3 details the research design and methodology employed across both studies, while Chapter 4 presents the questionnaire, ranking, physiological, and qualitative results. Chapter 5 evaluates these findings in relation to the research questions, discusses their place within the broader research context, and addresses the study's limitations. Finally, Chapter 6 summarises the thesis's key contributions and outlines avenues for future research.

Chapter 2

Related Work

This chapter reviews the literature relevant to personal space regulation in VR. It begins by tracing the developments of immersive technologies from early conceptual work through successive commercial cycles, before examining how this evolution gave rise to social VR as a distinct research domain. The chapter then considers social immersive platforms, proxemics and personal space invasion within psychology before addressing the intersection of these fields. Finally, it reviews the countermeasures currently employed or under investigation in this context.

2.1 Immersive Technologies

Perlin [2016] argues that virtual reality has entered the later phase of the "long nose of innovation", a phrase Buxton [2008] introduced to describe the decades that technologies may require before achieving broad consumer acceptance. Against this backdrop, the present thesis focuses on interpersonal interaction rather than technological capability, reflecting the growing importance of refining user experiences as immersive technologies mature. The conceptual roots of virtual reality can be traced to *Pygmalion's Spectacles* by Weinbaum [1935]; practical virtual reality systems, however, did not emerge until several decades later. Among the

Early VR concepts trace to the mid-1930s

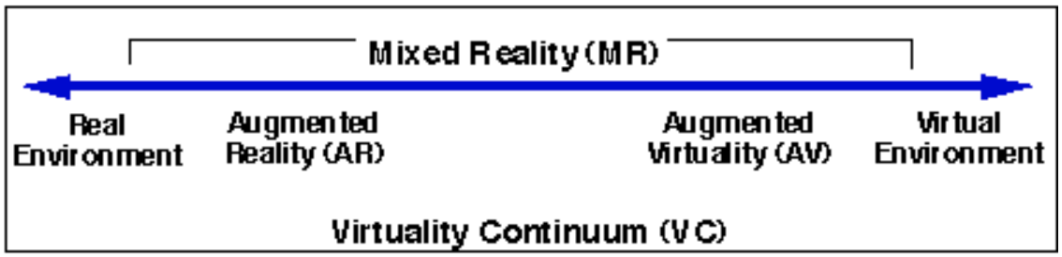


Figure 2.1: Reality–virtuality continuum proposed by Milgram and Kishino [1994].

Earliest practical VR systems

earliest practical developments were Morton Heilig's *Telesphere Mask*[1] and *Sensorama Simulator*[2], both introduced in the early 1960s. A further milestone came with the *Sword of Damocles*, introduced by Sutherland [1968] and widely regarded as the first HMD.

Coining of the terms VR and AR

These technological advances set the stage for immersive systems, while researchers simultaneously started to formalise the concepts and terminology used to describe them. In this context, the term *virtual reality* (VR) was popularised by Lanier [1992]: it generally refers to computer-generated interactive 3D environments that produce a sense of spatial presence [Bryson, 2013]. The closely related term *augmented reality* was first coined in 1992 by Boeing researchers to describe systems that overlay digital information onto the physical world [Janin et al., 1993].

Reality-Virtuality Continuum

Building upon these definitions, the reality–virtuality continuum, proposed by Milgram and Kishino [1994] and depicted in Figure 2.1, conceptualises a spectrum that extends from the physical world, governed by the laws of physics, to entirely virtual environments. Positioned between these two extremes are augmented reality (AR) and *augmented virtuality* (AV), which represent varying degrees of integration between real and digital content. Collectively, these intermediate environments constitute *mixed reality* (MR), encompassing all experiences that combine real and virtual elements to varying degrees.

[1] `https://patents.google.com/patent/US2955156` [Accessed: April 2026]

[2] `https://patents.google.com/patent/US3050870A` [Accessed: April 2026]

2.1.1 Maturation of Immersive Technologies

In Buxton's model of the long nose of innovation, the refinement and augmentation phase describes a period in which technological advances were largely confined to research and specialist applications. During this phase, the military became one of VR's most prominent application domains, developing flight simulators, such as the *Super Cockpit*, to train pilots in immersive environments [Furness, 1986]. Simultaneously, developments in interaction and immersion technologies also continued. For instance, Zimmerman et al. [1986] introduced hand tracking as a way of interacting with virtual environments through the *DataGlove*. The *Cave Automatic Virtual Environment* (CAVE), took a different approach: rather than relying on an HMD, it projected stereoscopic imagery in a room-sized space [Cruz-Neira et al., 1992]. Together, these developments advanced immersive interaction techniques, though complexity and cost continued to limit VR to specialised domains.

VR restricted to niche uses during the refinement phase

Immersion and interaction advances

In the 1990s, VR moved from research laboratories into the commercial market, entering what Buxton calls the productisation phase. During this period, Nintendo released the Virtual Boy [Zagal and Edwards, 2024], and Disney opened DisneyQuest [Fisher, 1999], both of which signalled interest in immersive technologies within the gaming and entertainment industries. Despite this momentum, these efforts did not achieve sustained commercial success. Partly, VR headsets of the period were expensive and technologically limited and many users reported discomfort, headaches, and cybersickness after use [Biocca, 1992; McCauley and Sharkey, 1992; Kao et al., 2020]. Moreover, the industry lacked the infrastructure to manufacture, distribute and support these systems at scale [Dzardanova and Kasapakis, 2022]. By the end of the decade, the optimism surrounding VR's first commercial wave had given way to a prolonged decline.

VR's transition into the consumer market

Multiple factors led to VR's early setback

Despite the decline in consumer interest during the late 1990s and early 2000s, research and development in VR and AR continued within specialised domains including medicine, defence, and clinical psychology. In these fields,

Research persisted despite commercial decline

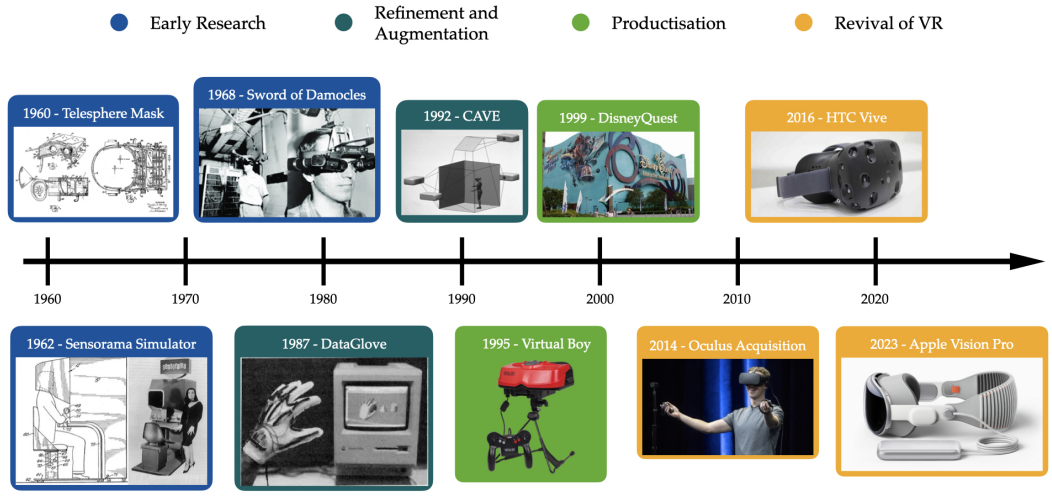


Figure 2.2: Timeline of key milestones in immersive technologies, organised according to Buxton's long nose of innovation and extended with the revival of VR.

immersive technologies were adopted for applications such as surgical training [McCloy and Stone, 2001], anatomical visualisation [Falah et al., 2014], and military simulation [Livingston et al., 2002; Lele, 2013], as well as the treatment of post-traumatic stress disorder [Roy, 2006], phobias, and eating disorders [Riva, 2003]. Meanwhile, ongoing advances in VR hardware, simulation techniques, and interaction design gradually laid the technological foundation for the subsequent consumer revival.

Revival of consumer VR

A major turning point came in 2014, when Facebook acquired Oculus VR for approximately USD 2 billion[3], signalling renewed industry confidence in immersive technologies. Subsequent consumer releases, including the HTC Vive[4], expanded access to VR; Apple's more recent Vision Pro[5] marks a further step towards mixed-reality integration. As Figure 2.2 illustrates, the long refinement phase

[3] `https://about.fb.com/news/2014/03/facebook-to-acquire-oculus/` [Accessed: April 2026]

[4] `https://www.vive.com/eu/newsroom/2016-01-04/` [Accessed: April 2026]

[5] `https://www.apple.com/newsroom/2023/06/introducing-apple-vision-pro/` [Accessed: April 2026]

spanning several decades contrasts sharply with the rapid acceleration of milestones from 2012 onwards, underscoring how quickly the conditions for social VR emerged once consumer hardware became viable. This revival has supported the growth of large-scale social VR, while raising new questions about their long-term sustainability.

Across these cycles of commercial optimism and decline, the growing social orientation of immersive technologies has consistently shifted research attention towards interpersonal interaction. Consequently, understanding how users negotiate interpersonal space has become an increasingly important challenge for the design of social virtual environments. The following section, therefore, examines the emergence of social VR and the interactional challenges associated with these environments.

Social interaction became central to VR

2.1.2 Social VR Platforms

> *"Oculus has the chance to create the most social platform ever, and change the way we work, play and communicate."*
>
> *—Mark Zuckerberg (2014)*

The commercial revival of VR in the mid-2010s was accompanied by a decisive shift towards social interaction as a primary use case, with social interaction becoming central to VR applications [Dzardanova et al., 2024] and introducing new challenges for interpersonal behaviour in shared virtual spaces. Social VR platforms enabled users to interact within embodied shared spaces: they could form social connections [Zamanifard and Freeman, 2019], engage in varied activities [Maloney and Freeman, 2020], explore alternative forms of self-presentation [Freeman and Maloney, 2021], and participate in collaborative or recreational experiences [Montagud et al., 2022; Piitulainen et al., 2022]. This range of interaction distinguishes social VR from traditional social networking platforms. HMDs further reinforced this sense of embodiment, supporting more embodied ways of interaction [Maloney et al., 2021]. Figure 2.3

Social VR enables embodied interaction and connection



Figure 2.3: Examples of contemporary social VR platforms, illustrating embodied avatars, shared virtual environments, and social interaction.

depicts several prominent social VR platforms, illustrating the embodied avatars and shared virtual spaces that characterise this mode of interaction.

Embodied co-presence in social VR

Unlike conventional online social platforms, social VR environments provide users with a sense of embodied co-presence, creating the impression of occupying the same physical space as others despite being geographically separated. Maloney et al. [2021] attribute this experience to embodied avatars that convey users' movements and gestures in real time, immersive three-dimensional environments enabled by six-degree-of-freedom tracking, and multiple channels of verbal and non-verbal communication. Together, these characteristics allow interactions to resemble face-to-face encounters more closely than traditional forms of computer-mediated communication [Wei et al., 2024]. Social VR interactions can therefore evoke social and emotional responses similar to those experienced during face-to-face encounters, leading users to perceive virtual interactions as meaningful and consequential [Freeman and Acena, 2021].

Social VR can elicit real social responses

While these characteristics enable rich social experiences, they also create opportunities for harassment and interpersonal boundary violations that can feel personally consequential despite occurring in a virtual environment [Freeman et al., 2022]. Understanding why such violations are psychologically relevant requires first examining the theoretical mechanisms through which virtual interactions come to feel real.

Potential for harassment in social VR

2.1.3 Presence and Embodiment in Social VR

Two theoretical concepts, presence and embodiment, help explain why interpersonal events in social VR are experienced as psychologically real; together, they provide the foundation for understanding why personal space violations in these environments are not merely virtual. Presence provides a critical theoretical foundation for understanding why social VR interactions carry psychological weight. Slater [2009] proposed that immersive virtual environments produce two interrelated illusions: the *Place Illusion*, or the sense of actually inhabiting the virtual space, and the *Plausibility Illusion*, or the sense that events within that space genuinely refer to the user. Together, these illusions can elicit realistic behavioural and physiological responses to virtual stimuli, even when users remain aware that the environment is not real.

Presence and embodiment underpin realistic social VR interactions

Slater et al. [2022] subsequently identified *Embodiment* as a third component. The sense of embodiment encompasses body ownership, self-location, and agency, with agency referring to the experience of controlling one's actions through the virtual body [Kilteni et al., 2012]. In social VR, users interact through embodied avatars that replicate their movements in real time; interpersonal events are therefore experienced as happening to the user rather than merely to an avatar.

Embodiment theory corroborates social VR interactions

These characteristics have important implications for interpersonal behaviour in social VR. Because embodied interactions are experienced as being directed towards the user, personal space violations can be perceived as gen-

Embodiment preserves proxemic responses in social VR

uine social transgressions rather than merely virtual events. Consequently, such violations have been revealed to evoke feelings of discomfort, unsafety, and harassment [Freeman et al., 2022], indicating that proxemic principles established in physical environments continue to govern behaviour in immersive virtual environments. This theoretical foundation motivates the following section, which introduces proxemics as the framework for understanding interpersonal distance and personal space.

2.2 Proxemics

Hall's theory of proxemics

While early immersive technologies were emerging, Hall [1963] introduced proxemics, a theory that examines how interpersonal distance functions as a form of nonverbal communication. Building on this work, Hall [1966] identified four interpersonal distance zones, as illustrated in Figure 2.4, scaled to an individual of average height to give a concrete sense of the interpersonal distances involved. These zones could each be further divided into close and far ranges, and correspond to different degrees of social intimacy and interaction. However, Hall [1966] emphasised that these distances should not be regarded as universal: they were derived primarily from observations of middle-class North American adults and may vary across cultural and social contexts.

Personal space is shaped by multiple factors

Following Hall's foundational work, proxemics research expanded to examine the factors that interpersonal distance preferences, including culture [Aiello and Thompson, 1980; Baldassare and Feller, 2009], age [Fry and Willis, 1971], and gender [Fisher and Byrne, 1975; Skolnick et al., 1977]. These studies indicate that personal space is not fixed; rather, it varies according to individual, social, and situational factors. Building on this understanding, subsequent research investigated the psychological consequences of violating preferred interpersonal distances.

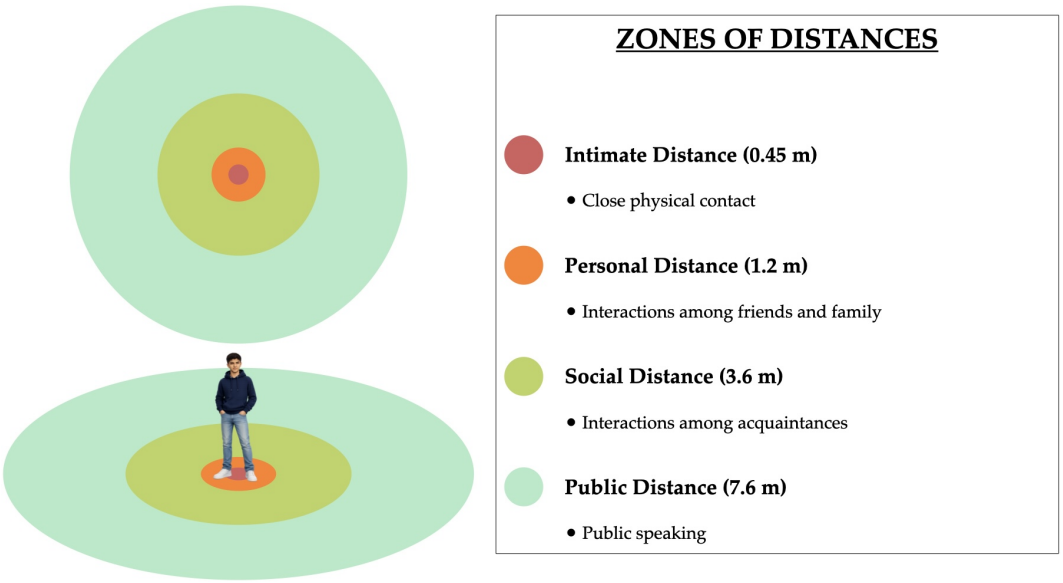


Figure 2.4: Visualisation of the proxemic zones defined by Hall [1966], comprising intimate, personal, social, and public space. The human figure represents an individual 175 cm tall, with the illustrated proxemic zones scaled accordingly.

2.2.1 Personal Space Invasion

Origins of personal space invasion research

Felipe and Sommer [1966] were among the earliest to examine violations of interpersonal distance, introducing the concept of *personal space invasion* (PSI). In their study, students were instructed to sit in very close proximity to another student. Their observations indicated that an unusually close approach by an unfamiliar individual in a public setting elicited signs of discomfort and often prompted individuals to withdraw from the situation. These findings provided early empirical evidence that violations of preferred interpersonal distances can influence both emotional states and social behaviour.

Reactions to PSI vary across individuals and social contexts

Subsequent research extended these early findings by investigating both the consequences of PSI and the factors that influence individuals' responses. PSIs have been found to induce stress [Kanaga and Flynn, 1981]. Beyond the invasion itself, the manner in which an intrusion occurs also influences how it is perceived: Sundstrom and Sundstrom [1977] found that seeking permission before enter-

ing another person's personal space altered participants' responses, while Fisher and Byrne [1975] reported that reactions also varied according to gender, as they observed lone males to erect barriers against face-to-face invasions, whereas females to erect barriers against adjacent invasions. Together, these findings suggest that the experience of PSI is shaped by both individual characteristics and the social context in which the interaction occurs.

SCR as an objective measure of PSI

Researchers have also examined the physiological correlates of PSI using the *skin conductance response* (SCR), a measure of *electrodermal activity* (EDA) that reflects sympathetic nervous system arousal [Babaei et al., 2021]. Candini et al. [2021] associated SCR with individuals' preferred interpersonal distance, establishing it as an objective complement to self-report measures. Notably, this response also extends to virtual encounters: Llobera et al. [2010] and Tootell et al. [2021] reported systematic increases in SCR as virtual agents approached participants in immersive VR environments, mirroring responses observed in physical settings. Together, these findings support the use of skin conductance as an objective complement to subjective measures when investigating PSI in immersive virtual environments.

Proxemics extended to HCI domains

The growing recognition that interpersonal distance shapes human behaviour led HCI researchers to adopt proxemic principles. Greenberg et al. [2014] argued that spatial relationships between users and technology could support more natural forms of interaction across a range of interactive systems. This perspective subsequently influenced research in emerging domains such as human–robot interaction [Stark et al., 2018] and virtual environments [Nassiri et al., 2010], where interpersonal distance became an important consideration in interactions with embodied agents. Social VR further extends this work by enabling researchers to study proxemics between embodied users who share the same virtual space. Overall, these findings establish that personal space behaviour, and the psychological and physiological consequences of its violation, are not confined to the physical world, a foundation that directly motivates the investigation of proxemics in virtual environments.

2.3 Proxemics Research in Virtual Reality

Early research on proxemics in virtual environments asked whether interpersonal distance preferences observed in the physical world would also manifest in VR. Bailenson et al. [2003] conducted one of the most influential studies in this area, examining users' responses to both passive and active approaches by virtual agents. Participants respected the personal space of virtual characters: they maintained greater distances when approached from the front rather than from behind and when engaging in mutual gaze. Furthermore, participants preferred greater interpersonal distance from computer-controlled virtual agents than from human-controlled virtual avatars, suggesting that proxemic behaviour in virtual environments is influenced by both social cues and the perceived nature of the partner.

Personal space preferences persist in VR

After researchers had established the existence of personal space in virtual environments, they increasingly examined the factors that influence its extent and regulation. As in physical-world proxemics, interpersonal distance preferences in VR vary according to both the individual and interaction with the partner. Kim and Sung [2024] corroborated the findings of Bailenson et al. [2003], observing that participants maintained substantially greater interpersonal distances in the virtual world than in comparable physical-world interactions. Subsequent studies have further confirmed that these preferences are shaped by the virtual interaction partner's characteristics. For example, Buck et al. [2020] found that personal space boundaries depend on the appearance of the approaching entity, while Iachini et al. [2016] and Kimoto et al. [2023] reported that factors such as avatar appearance, age, and gender influence interpersonal distance preferences.

Personal space in VR is shaped by factors similar to those in the physical world

Bönsch et al. [2018] similarly found that interpersonal distance in a CAVE-based virtual environment varied according to the emotional expression and number of approaching virtual agents. Participants maintained greater distances from angry agents and groups than from happy or solitary agents, reinforcing the idea that proxemic be-

Social and contextual cues shape proxemics in VR

haviour in virtual environments remains sensitive to social and contextual cues.

PSI countermeasures differ from ambient social cues

More recently, Nelson et al. [2024] revealed that approaching users adapt their behaviour in response to the proximity and gestures of virtual characters. Personal space countermeasures, however, differ from these ambient social cues in that they constitute intentional interventions. Whether approaching users perceive and respond differently to such interventions remains unexplored.

Motivation for personal space countermeasures

With the emergence of social VR platforms, managing interpersonal distance has become an increasingly important design challenge. Personal space regulation has been closely linked to users' privacy, safety, and overall experience in immersive environments [Falchuk et al., 2018]. At the same time, reports of harassment and other unwanted behaviours in social VR have increased the need for effective mechanisms that protect users from personal space violations [Blackwell et al., 2019]. These concerns have motivated both researchers and platform developers to investigate countermeasures for preventing, communicating, and responding to PSI.

2.4 Prevailing PSI Countermeasures

Preventative and reactive countermeasures

Although the literature does not formally distinguish between different classes of personal space countermeasures, the approaches reviewed here can be organised according to the point at which they intervene. Some seek to prevent personal space violations before they occur by establishing or communicating personal space boundaries; others respond once a PSI is imminent or already underway.

Protected personal space boundaries in social VR

One of the most widely adopted preventive approaches establishes a protected boundary around the user. Personal space bubbles, or safety bubbles, create a virtual region that discourages or prevents unwanted proximity before direct interaction becomes possible. Several commercial platforms have adopted this type of mechanism, includ-

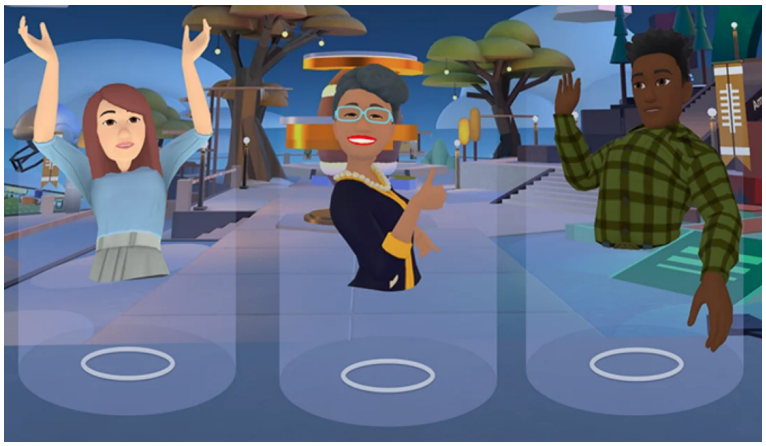


Figure 2.5: Implementation of personal safety bubbles in Meta Horizon Worlds, illustrating protected zones around user avatars that restrict close interpersonal proximity.

ing Meta Horizon Worlds[6], as depicted in Figure 2.5. User feedback suggests that safety bubbles are generally well received: in the study by Freeman et al. [2022], participants reported that they helped protect personal space and reduce experiences of harassment.

Research on protective boundary design

Alongside commercial implementations, researchers have explored alternative designs for protective personal space boundaries. Nassiri et al. [2009], for example, proposed invisible protective bubbles that become visible when external objects come into contact with them and can be activated or deactivated by users as needed. More recently, LaRubbio et al. [2023] investigated whether the bubble geometry affects perceived protection, comparing cylindrical, polygonal, and body-shaped designs. Their findings revealed no significant differences among these geometries, suggesting that the presence of a protective boundary may matter more than its specific shape.

Rather than establishing protective boundaries, other approaches regulate access to another person's personal space once interaction becomes unwanted. Many platforms therefore provide mechanisms that interrupt, block, or oth-

[6] `https://mashable.com/article/meta-personal-boundary-horizon-worlds-facebook` [Accessed: May 2026]



Figure 2.6: Stop gesture in Rec Room, allowing users to block and mute unwanted interactions with other avatars.

Interaction-based personal space protection in social VR

erwise regulate unwanted interactions. For example, Rec Room[7] allows users to block other players through a stop gesture (see Figure 2.6). At the platform level, Microsoft introduced private social hubs in AltspaceVR to reduce users' exposure to harassment and other disruptive behaviours[8].

Research on reactive personal space countermeasures

Beyond commercial platforms, researchers have explored a variety of mechanisms for responding to PSIs. Sun et al. [2021] compared several methods for stopping approaching virtual agents, including gradual deceleration, forced stopping, visual warnings, and temporary pauses. Participants generally preferred interventions that immediately halted an approaching agent; pause-based techniques were viewed less favourably. Here too, however, the countermeasure was evaluated from the standpoint of the user being approached, rather than the approaching user. Pohl and Achtelik [2019] similarly proposed multi-level personal space controls: rather than a single restriction, users could specify which objects or avatars may enter different personal space zones.

[7] `https://www.youtube.com/watch?v=2bWTgmAxBes` [Accessed: May 2026]

[8] `https://techcrunch.com/2022/02/16/microsoft-shuts-down-altspacevrs-social-hubs-to-combat-harassment/` [Accessed: May 2026]

Blehm's comparative evaluation of PSI countermeasures

Blehm [2025] conducted a comparative evaluation of three representative countermeasures: SAFETY BUBBLE, MOVE, and BLOCK. In this study, participants encountered approaching avatars and activated a countermeasure whenever they felt uncomfortable with the remaining interpersonal distance. Alongside subjective feedback, Blehm [2025] measured physiological responses using skin conductance to assess emotional arousal. The findings indicated that personal space countermeasures generally improved user experience and reduced the negative effects associated with PSI. However, participant preferences varied considerably across participants; no single countermeasure was universally preferred, and users may benefit from access to multiple protection mechanisms. The evaluation nevertheless remained centred on the perspective of the user whose personal space was being violated, leaving the approaching user's experience unexplored.

Research focused only on the protected user

Agency offers an unexplored perspective on countermeasures

Whereas body ownership has primarily explained responses to personal space violations, the agency component of embodiment offers a complementary perspective on the approaching user's experience [Kilteni et al., 2012]. Personal space countermeasures do not threaten the virtual body in the same way as an intrusion might; rather, they interrupt intended actions and may therefore influence the user's sense of agency. Whether this distinction shapes approaching users' responses remains unexplored.

Negotiation-based personal space regulation

Across the countermeasures reviewed here, the approaching users' own experience has received little direct attention. One notable exception is the work of Wang et al. [2025], who proposed a negotiated user-to-user teleportation framework that allows users to approve or deny spatial access before another user enters their vicinity. This principle of negotiated access mirrors earlier findings by Sundstrom and Sundstrom [1977], who found that requesting permission before entering another person's personal space influenced how the intrusion was perceived in physical-world interactions. Yet even this work concerns granting access rather than how an approaching user perceives a countermeasure once it acts on them.

Approaching users' perception of countermeasures remains unexplored

Hence, to the best of our knowledge, research on PSI and its countermeasures in social VR has been almost exclusively conducted from the perspective of the user whose personal space is being violated. Whether these interventions are experienced as fair, justified, or acceptable from the approaching side, and whether the same countermeasure is perceived differently depending on which role a user occupies, remains open.

Research gap and thesis contribution

Building on the countermeasures developed by Blehm [2025], this thesis addresses this gap by investigating personal space countermeasures from the approaching user's perspective, for whom, unlike the protected user, countermeasures may interrupt intended actions rather than respond to a perceived PSI. In addition, it examines how these established countermeasures are perceived across both interaction roles, providing a comparative perspective that has not previously been explored.

Chapter 3

Methodology

This chapter describes the methodology adopted in this thesis and the design decisions underlying both studies. It first introduces the shared experimental setup: the virtual environment, locomotion, and PSI countermeasures adapted from Blehm [2025]. The chapter then presents the methodology of Study 1 and Study 2 in sequence, covering each study's designs, participant recruitment, data collection procedures, and pilot testing.

3.1 Shared Experimental Platform

The experimental platform used throughout this thesis was based on Blehm's application, developed for the Apple Vision Pro using Xcode and Reality Composer Pro and deployed on visionOS. Adobe Mixamo[1] was used to create the virtual human animations, including idle, walking, blocking, and turning behaviours, which were subsequently integrated into the virtual environment. Although the original application investigated PSI countermeasures in an AR setting, this thesis adapted it for a fully immersive VR environment by introducing a new virtual environment, thereby modifying the interaction mechanics and extending the experimental procedures.

Application adapted for immersive VR from Blehm [2025]

[1] `https://www.mixamo.com/` [Accessed: February 2026]

Definition of the invader and invadee roles

Within the context of PSI, this thesis distinguishes between two distinct roles. Throughout this thesis, the individual who approaches and enters another person's personal space is referred to as the *invader*, and the individual whose space is entered as *invadee*. Although invadee is not a standard dictionary term, it is used throughout this thesis as a counterpart to invader.

VR application adapted for active interaction and countermeasure evaluation

The adapted application served as the common experimental platform for both studies presented in this thesis. Blehm's application investigated PSI countermeasures from the invadee's perspective; in this thesis, the platform was adapted so that participants could actively approach virtual characters and experience the implemented countermeasures from the invader's perspective. Although both studies of this thesis shared the same underlying system and core interaction mechanics, minor adaptations were introduced to accommodate their respective research objectives. The following sections describe the virtual environment, locomotion, and PSI countermeasures implemented within the system.

3.1.1 Virtual Environment

Selecting a realistic yet controlled virtual environment

This subsection describes the design of the shared virtual environment, covering the selection criteria that guided the choice of setting and the resulting virtual office corridor developed for use across both studies. Before implementing the virtual environment, several environmental concepts and interaction scenarios were considered. Candidate settings included private environments, such as a reception area, waiting room, library corridor, and office, as well as more public spaces, including a park and museum. The selection was guided by two competing requirements: the environment needed to create a realistic interpersonal encounter while maintaining a high degree of experimental control. It also had to support repeated interactions between users, provide a plausible context for approaching another person, and minimise distractions unrelated to the PSI countermeasures under investigation.

Design criteria for the virtual environment

Irrespective of the final setting, several criteria guided the virtual environment design. The environment needed to support repeated and reproducible interpersonal encounters while balancing experimental control with ecological validity. At the same time, it had to provide a natural context in which participants could approach another individual without both users remaining continuously visible throughout the interaction. To achieve this, the environment was designed around an L-shaped layout: participants entered the interaction space by turning a corner before approaching the other individual. This layout more closely resembled naturally occurring encounters in everyday environments while ensuring that each interaction began in a consistent and reproducible manner.

L-shaped layout for consistent interactions

Office corridor selected for plausible and controlled interactions

Based on these considerations, an office environment was selected. The virtual environment was modelled after the institute's office corridor and closely resembled the physical surroundings in which the studies were conducted. By recreating a familiar real-world setting, the design aimed to enhance ecological validity and strengthen the plausibility illusion of the virtual scenario, thereby encouraging natural behaviour during interpersonal encounters. Furthermore, the corridor accommodated the desired movement path, enabling participants to approach another individual in a controlled and reproducible manner.

Corridor dimensions informed by architectural guidelines

The environment was created in Reality Composer Pro. Architectural guidelines for buildings in North Rhine-Westphalia informed the corridor dimensions. The corridor measured approximately 14 m in length, 2 m in width, and 2.4 m in height, with the ceiling height matching the minimum specified in the *Bauordnung für das Land Nordrhein-Westfalen*[2]. Although these regulations specify a minimum width of 1.2 m for escape-route corridors, the width was increased to 2 m to provide participants with greater freedom of movement and to facilitate more natural interpersonal interactions. The corridor length provided sufficient walking distance before participants reached the interaction area, while maintaining the proportions typical of an office corridor.

[2] `https://recht.nrw.de/gvnrw/2016-s1162/` [Accessed: December 2025]



Figure 3.1: Virtual office corridor environment developed for the studies.

Four-office layout strengthens environmental realism

To reinforce the office setting, the corridor was connected to four small offices, two on each side, and furnished with freely available 3D assets from Sketchfab. Table A.2 provides a complete list of the utilised assets. As Figure 3.1 depicts, the corridor's proportions and furnishings closely resemble a typical office environment, supporting the plausibility illusion central to the study's cover story. Having established the environment's design, the following subsection describes the locomotion and interaction techniques used to navigate it.

3.1.2 Locomotion and Interaction

Navigation used through controller-based locomotion

Participants navigated the virtual environment using a handheld game controller. Controller-based locomotion was selected for two reasons: it allowed participants to traverse the full length of the virtual corridor, and it kept the movement technique consistent across all trials without constraining participants to the available laboratory space. Study 1 used an Xbox controller, and Study 2 employed a PlayStation 4 controller. This difference reflected the hardware available at the time of each study and did not affect the implemented locomotion or interaction mechanics.

The left thumbstick controlled continuous locomotion, allowing participants to move forwards, backwards, and sideways. In the terminology by Zhai [1996], this corresponds to a rate-control transfer function because thumbstick displacement determines movement rate rather than directly specifying a target position. To ensure consistent navigation throughout the experiment, movement was constrained to the virtual corridor, preventing participants from leaving the experimental area.

Left thumbstick controls locomotion

The right thumbstick controlled orientation within the virtual environment. This can be characterised as a position-control transfer function because the thumbstick specifies the desired change in viewing direction [Zhai, 1996]. The Apple Vision Pro's integrated head tracking complemented this control scheme, allowing participants to inspect their surroundings by moving their heads.

Right thumbstick controls orientation

Although the specific interaction tasks differed between the two studies and are described in the corresponding study-design sections, the invader-perspective interaction followed the same underlying principle in both studies. Participants navigated the virtual environment by approaching a virtual human; once they reached the predefined distance threshold, the implemented PSI countermeasures activated.

Approaching users trigger countermeasures

3.1.3 Implemented PSI Countermeasures

The experimental conditions investigated in this thesis were adapted from the work of Blehm [2025]. While Blehm's original study examined the implemented countermeasures from the invadee's perspective, the present work evaluates them from the invader's perspective. Four conditions were investigated: BASELINE, SAFETY BUBBLE, EVADE, and PUSH. The latter two correspond to the MOVE and BLOCK conditions proposed by Blehm [2025], but they were renamed to better reflect the behaviour experienced from the invader's perspective.

Four PSI countermeasure conditions investigated throughout this thesis

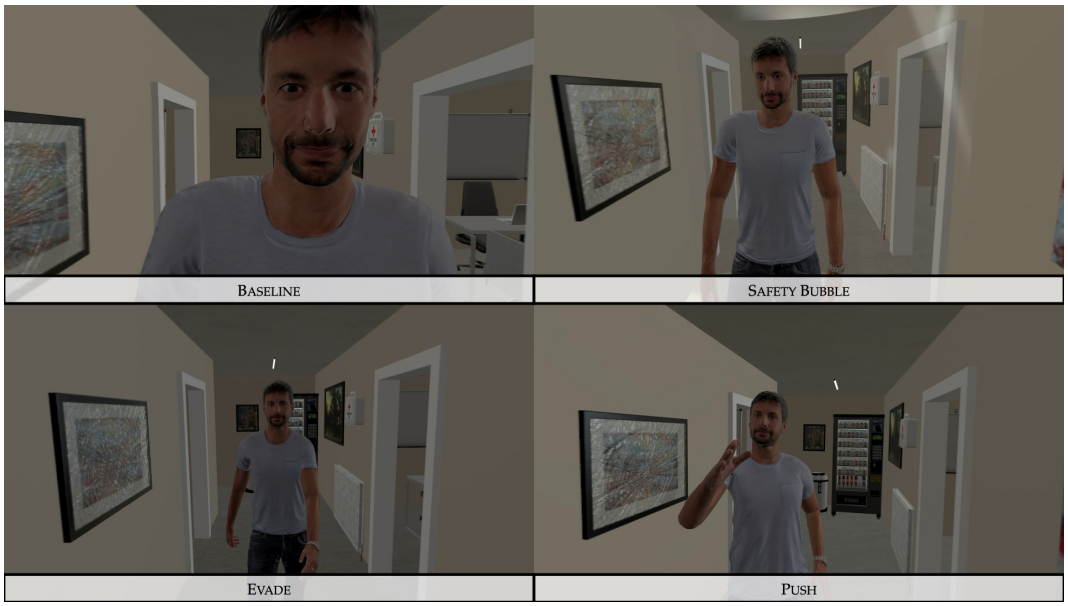


Figure 3.2: Invader's view of the four experimental conditions, comprising BASELINE, SAFETY BUBBLE, EVADE, and PUSH.

As Figure 3.2 illustrates, the three active conditions differ markedly from the BASELINE in the visual or physical response they impose: the SAFETY BUBBLE communicates the violated boundary, the EVADE condition prompts retreat, and the PUSH condition exerts direct physical force, representing three points on a spectrum from communicative to coercive intervention.

Participant familiarisation before the experiment

Before completing the experimental conditions, participants undertook a familiarisation scenario that introduced the virtual environment, locomotion, and interaction mechanics. They first received time to navigate the virtual corridor and become comfortable with the controller-based locomotion. Once familiar with the movement controls, they could summon a virtual human positioned approximately 5 m away, which provided a reference for interpersonal distance and the virtual environment's spatial scale. Participants could repeat both stages as often as desired before the experiment began. As this served solely as a training phase, the familiarisation phase was excluded from the experimental trials.

Countermeasures activated at a 1.2 m interpersonal distance

Across all experimental conditions, the system continuously monitored the interpersonal distance between the participant and the virtual human. In the active countermeasure conditions, activation occurred at an interpersonal distance of 1.2 m, corresponding to the outer boundary of the personal distance zone defined by Hall [1966]. Upon activation, the system briefly suspended participant locomotion before executing the respective countermeasure. The accompanying Git repository provides demonstration videos of the familiarisation phase and all experimental conditions for both studies. The individual experimental conditions are described below.

Baseline

BASELINE Condition

The BASELINE condition served as the control condition and did not implement an active PSI countermeasure. Participants could therefore approach the virtual human without eliciting a visual or behavioural response.

Safety Bubble

SAFETY BUBBLE Condition

The SAFETY BUBBLE condition visualised the virtual human's personal space using a semi-transparent cylindrical boundary surrounding the character. In line with the invisible protective bubbles proposed by Nassiri et al. [2009], this boundary remained hidden during normal interaction and became visible when the participant entered the personal space threshold. The countermeasure therefore communicated the limits of acceptable interpersonal distance.

Evade

EVADE Condition

The EVADE condition represented an avoidance response to a PSI. When the participant entered the personal space threshold, the virtual human walked backwards to reestablish interpersonal distance, emulating a common response to an unwanted approach.

Push

PUSH Condition

The PUSH condition represented a direct response to a PSI. When the participant entered the personal space threshold, the virtual human performed a pushing gesture that redirected the participant sideways and increased the interpersonal distance between both individuals. This behaviour represented an active attempt to re-establish personal space following the intrusion.

Experimental conditions represent different intervention strategies

Together, the four conditions represent a spectrum from no intervention in the BASELINE, through a communicative response that signals a crossed boundary SAFETY BUBBLE and a social avoidance response EVADE to a direct physical intervention PUSH, providing a structured basis for comparing invaders' responses across qualitatively different approaches to personal space regulation.

3.2 Study 1: Evaluation of the Invader's Perspective

Overview of the Study 1 design

Having described the common experimental setup, this section details Study 1's design and procedure. Prior to the experiment, participants were informed that they would participate in a social VR scenario involving interactions with other users in a shared virtual environment. This framing established a social context for the encounters and encouraged participants to interpret the virtual humans as other users rather than solely as scripted virtual agents. Within this scenario, participants approached individuals in a virtual office environment while encountering the implemented PSI countermeasures as part of realistic interpersonal interactions in social VR. The following subsections describe the individual components of the study design, participant recruitment, data collection, and pilot testing.

3.2.1 Study Design

Within-subjects experimental design of Study 1

Study 1 employed a within-subjects design in which 24 participants experienced all four experimental conditions, allowing each participant to directly compare the different approaches to personal space regulation while reducing inter-participant variability. Each condition was presented once, producing four trials per participant; after each trial, participants completed a questionnaire assessing their experience of the encountered condition.

Study Mascot	Condition 1	Condition 2	Condition 3	Condition 4
Dog	BASELINE	EVADE	PUSH	BUBBLE
Eagle	BASELINE	EVADE	BUBBLE	PUSH
Wolf	BASELINE	BUBBLE	EVADE	PUSH
Peacock	BASELINE	PUSH	EVADE	BUBBLE
Elephant	BASELINE	PUSH	BUBBLE	EVADE
Lion	BASELINE	BUBBLE	PUSH	EVADE

Table 3.3: Counterbalancing of the experimental conditions by study mascot.

Counterbalancing strategy

The experimental conditions were counterbalanced across participants to minimise potential order effects. The BASELINE condition was always presented first, providing a common reference interaction without an active countermeasure before participants encountered the remaining conditions. The three active countermeasure conditions then appeared in a counterbalanced order.

Random assignment of condition sequences

The experimenter implemented counterbalancing, by assigning all possible conditions to study mascots and printing them on individual chits. Before the experiment, participants randomly selected one of these chits, which determined the order in which they experienced the three active countermeasure conditions. Table 3.3 depicts the resulting counterbalancing scheme.

Participants' task in Study 1

The study was framed as a social VR experience situated within a busy office environment. Participants navigated through the virtual corridor towards a vending machine located at the end of the environment; during this task, they approached a virtual human acting as the invadee, whose position required them to eventually enter the invadee's

personal space. The same avatar appeared throughout all trials to ensure consistency across the conditions.

Cover story to establish a believable social VR scenario

A television screen mirrored the participant's view of the virtual environment, allowing the experimenter to monitor the study. Participants were informed the experimenter represented the invadee, who was purportedly participating through a Meta Quest headset. This cover story reinforced the impression that the virtual human represented another user rather than a scripted virtual character. In reality, the avatar's behaviour was pre-programmed and controlled by the experimental system; participants were debriefed accordingly after the completion of the study.

Supporting characters intended to strengthen the plausibility illusion

Randomised interaction scenarios

The environment included two additional virtual humans to create the impression of a populated workplace. These supporting characters either remained engaged in conversation near the end of the corridor or moved into nearby office rooms without interacting with the participant. Their appearance and behaviour were randomised using four different virtual characters and 30 predefined movement scenarios. The invadee entered the interaction area either from around the corner of the L-shaped corridor or from one of the adjacent office rooms at the far end of the corridor before moving to a predefined position in the centre of the corridor. These variations resulted in 360 possible scene configurations, reducing the predictability of individual interactions. Figure 3.4 depicts the study scenario immediately before the participant entered the invadee's personal space. When the participant reached the predefined distance threshold, the system activated the assigned experimental condition, as described in Chapter 3.1.3.



Figure 3.4: Study 1 scenario showing the invadee and two supporting virtual humans within the virtual office environment.

3.2.2 Participant Recruitment and Data Collection

Study 1 recruitment strategy

Recruitment combined convenience sampling and word-of-mouth recruitment. Initial recruitment involved directly contacting participants, who were then encouraged to share information about the study within their own social and professional networks. The study imposed no specific inclusion or exclusion criteria; all interested individuals were eligible to participate. Data collection occurred between 5 March 2026 and 10 March 2026.

Ethical and procedural safeguards for Study 1

The study protected participant anonymity by assigning each participant a unique four-character alphanumeric identifier for use throughout data collection and analysis. Prior to the study, the responsible ethics committee granted ethical approval, and all participants provided informed consent before participating in the experiment. To standardise the experimental procedure across participants, the experimenter followed a predefined study guide that documented each stage of the study. Appendix B includes the participant information sheet, informed consent form, and study guide.

Data collected using a questionnaire comprising demographic, condition-specific, and ranking sections

The questionnaire comprised a demographics section, four condition-specific sections, and a final ranking section. Participants completed the demographics section before the experiment, the condition-specific sections after each experimental condition, and the final ranking section after all conditions. The condition-specific sections were further divided into five subsections each and assessed participants' perceptions, emotional responses, self-reflection, perceived realism, and evaluations of the implemented countermeasure, and concluded with an open-ended comment field for additional feedback. All items employed a five-point Likert scale with the response labels provided by Iowa State University[3], ranging from *Strongly Disagree* to *Strongly Agree*. Participants completed the questionnaire through a custom-developed iPad application[4], which exported responses in JSON format. All questionnaire items, organised by section, are provided in Appendix B.

Additional collection of EDA data

Following Blehm [2025], the study recorded physiological responses using a skin conductance sensor to complement the questionnaire data. The experimenter attached the sensor to the index and middle fingers of the participant's non-dominant hand, which continuously recorded skin conductance throughout the experiment, providing an objective measure of physiological arousal during each trial.

Pilot testing prior to data collection

A pilot study was conducted to evaluate the virtual environment, study procedure, and questionnaire design. Feedback from the pilot phase informed several refinements to the experimental setup before data collection began. Among other changes, these refinements included adjustments to the position of the invadee during PSIs and to its behaviour following the activation of a countermeasure.

Together, these design decisions positioned Study 1 to provide quantitative evidence of invaders' responses to countermeasures, establishing the empirical basis for the more exploratory comparative investigation in Study 2.

[3] `https://www.extension.iastate.edu/documents/anr/likertscaleexamplesforsurveys.pdf` [Accessed: April 2026]

[4] The application is included in the accompanying Git repository for reuse and further development.

3.3 Study 2: Comparative Evaluation of Both Interaction Perspectives

While Study 1 examined personal space countermeasures from the invader's perspective, Study 2 adopted a comparative design in which participants experienced both the invader and invadee perspectives. This design was intended to encourage participants to reflect on the implemented countermeasures from both sides of a PSI and thereby support the development of mutually acceptable countermeasures and support mechanisms. To facilitate this comparison, participants completed two complementary scenarios: one from the perspective of the invadee and one from the perspective of the invader. The invadee-perspective scenario was adapted from the work of Blehm [2025], whereas the invader-perspective scenario was based on the design employed in Study 1. The following subsections describe Study 2's design, participant recruitment, experimental procedure, and data collection methods.

Overview of the Study 2 design

3.3.1 Study Design

Study 2 employed a within-subjects design in which 12 participants experienced all four experimental conditions from both the invadee and the invader perspectives. For each of the four experimental conditions described in Chapter 3.1.3, participants first completed the invadee-perspective scenario, followed by a corresponding invader-perspective scenario specifically adapted to provide a comparable interaction from the opposite perspective. The order of the experimental conditions was counterbalanced using the same procedure described in Study 1 and the scheme illustrated in Table 3.3.

Within-subjects experimental design of Study 2

As in Study 1, a television screen mirrored the participant's view, allowing the experimenter to monitor progress throughout the study. Study 2 retained the cover story from Study 1: participants were informed that the virtual human represented the experimenter, who was purportedly using a Meta Quest headset. As Figure 3.5 depicts, the mir-

Study 2 retained the cover story from Study 1



Figure 3.5: Participant during Study 2, with the participant's view mirrored to a television screen for experimenter monitoring throughout the session.

rored display allowed the experimenter to observe the participant's view in real time, ensuring consistent monitoring of the interaction without interrupting the participant.

Participants' Task in Study 2

Participants first assumed the role of the invadee and activated the assigned countermeasure once they felt uncomfortable with the approaching invader. They then completed the corresponding invader-perspective scenario, in which they approached the invadee until the assigned countermeasure was triggered. Unlike Study 1, no supporting virtual humans were present, and the invadee remained in a fixed position throughout the interaction. These adaptations were intended to reduce differences between the two scenarios so that participants could compare the implemented countermeasures from both perspectives under otherwise similar conditions. The procedure always presented the invadee-perspective scenario first, providing a consistent basis for participants' subsequent comparison and reflection on both roles during the written reflection and interview.

3.3.2 Participant Recruitment and Data Collection

Participant recruitment strategy for Study 2

As in Study 1, recruitment combined convenience sampling and word-of-mouth distribution. We initially contacted participants directly and encouraged them to share information about the study within their own social and professional networks. Unlike Study 1, however, Study 2 excluded individuals who had previously participated in studies investigating PSIs, including the study conducted by Blehm [2025], to minimise potential familiarity effects. Data collection occurred between 19 May 2026 and 23 May 2026. Similarly, the study pseudonymised participant data using unique four-character alphanumeric identifiers for use throughout data collection and analysis. To standardise the experimental procedure across participants, the experimenter followed a predefined study guide, and all participants provided informed consent prior to participation. The participant information sheet, informed consent form, and study guide used during Study 2 are provided in Appendix C.

Ethical and procedural safeguards for Study 2

Qualitative data collection through retrospective reflection

In contrast to Study 1, which primarily focused on quantitative measures, Study 2 adopted a more exploratory approach and placed greater emphasis on qualitative data collection. Data collection consisted of a demographics questionnaire, written reflections, and a semi-structured interview. The demographics questionnaire is provided in Appendix C. The study used a retrospective testing approach: after each experimental condition, participants had up to five minutes to document their reflections before proceeding to the next condition. After completing all experimental conditions, participants took part in a semi-structured interview discussing their experiences, preferences, and perceptions of the implemented countermeasures from both the invadee and invader perspectives. The interviews were audio-recorded and transcribed, and Chapter 4 describes the analysis procedure. The written reflections served as a memory aid during the interview; although collected, they were not included in the formal thematic analysis, as the semi-structured interviews provided richer, more detailed accounts of the same experiences.

Semi-structured interviews after all experimental conditions

Pilot study refined the reflection and interview procedure

Before the main study began, a pilot study evaluated the experimental procedure and qualitative data collection methods. Pilot feedback informed refinements to the retrospective reflection phase and the subsequent semi-structured interview. Among other changes, these refinements reduced the reflection period from six to five minutes and adjusted the transition between perspectives and the interview structure to support a smoother study procedure.

Together, the two studies provide complementary quantitative and qualitative data on invaders' experiences of PSI countermeasures, the results of which the following chapter reviews.

Chapter 4

Results

This chapter presents the results of the two studies described in Chapter 3. It is organised into two sections, each corresponding to one study and beginning with an overview of the participant demographics to provide context for the reported findings. The first section reports Study 1's quantitative results, including the questionnaire responses and skin conductance measurements. The second section reports Study 2's qualitative results, presenting the themes identified through thematic analysis alongside their associated codes and illustrative participant quotations. To improve readability, Appendix D provides the detailed statistical tables and the complete thematic analysis codebook, allowing the main chapter to focus on the principal findings.

4.1 Study 1 Results

Organisation of the Study 1 results

The results of Study 1 begin with an overview of participant demographics, then report the quantitative questionnaire results, followed by the ranking task. It then presents participants' qualitative comments to contextualise the quantitative findings. Finally, it examines the physiological responses recorded during the experiment using participants' skin conductance measurements.

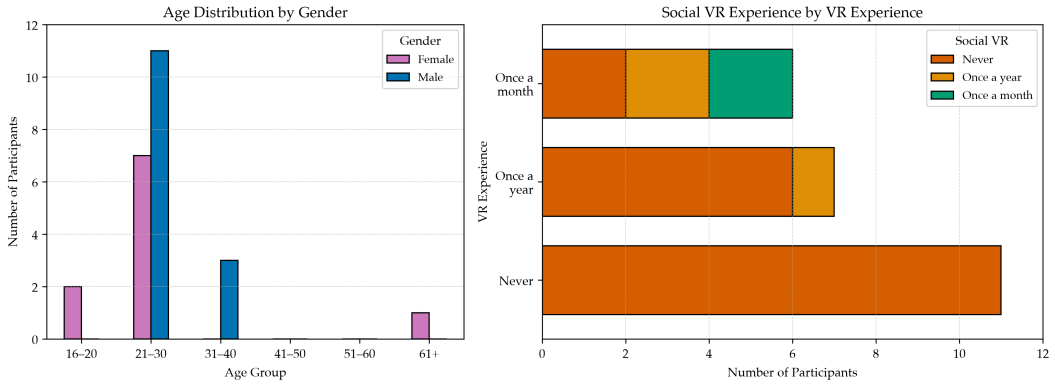


Figure 4.1: Study 1 participant demographics, including age and gender distribution and prior VR and social VR experience.

Study 1 participant demographics

A total of 24 participants participated in Study 1. Their ages ranged from 19 to 66 years (M = 26.96, SD = 9.54), with a median age of 24.5 years. The sample comprised 14 male and 10 female participants. Most participants were undergraduate or postgraduate university students from a range of disciplines, including computer science and dentistry, while a smaller number worked in professional or technical occupations. Prior VR experience varied across the sample, whereas social VR experience was generally limited. Figure 4.1 presents an overview of the participants' age and gender distribution, together with their prior VR and social VR experience.

VR familiarity varied; social VR familiarity was rare

4.1.1 Questionnaire Results

Shapiro–Wilk test indicated non-normality for all questionnaire data

This section presents the quantitative questionnaire responses collected after each experimental condition. To support reproducibility, the accompanying Git repository includes the Python scripts used for the statistical analyses, with Likert-scale responses mapped from 1 (*Strongly Disagree*) to 5 (*Strongly Agree*). Given the sample size, the Shapiro–Wilk test was used prior to the analyses to assess the normality of each questionnaire item. Because none of the Likert-scale responses met the assumption of normality, the quantitative analyses employed non-parametric statistical methods throughout.

Differences between the experimental conditions were evaluated using Friedman tests for repeated measures. Where a Friedman test identified a statistically significant overall effect, Bonferroni-corrected pairwise Wilcoxon signed-rank tests were performed to determine which conditions differed from one another. Table D.1 provides an overview of the Friedman test results for all questionnaire items; the corresponding post-hoc comparisons are reported within each questionnaire category.

Friedman tests with Bonferroni-corrected post-hoc comparisons

Perception

The questionnaire's `Perception` section assessed how participants interpreted the virtual avatar's response to their approach. It comprised four items: *Appropriate*, *Clear Reasoning*, *Easy to Understand*, and *Fair Reaction*. These items collectively evaluated whether participants considered the avatar's response appropriate for the situation, understood the response itself, perceived its underlying reasoning as clear, and regarded it as a fair reaction to their behaviour.

Four `Perception` questionnaire items

Figure 4.2 illustrates that the PUSH condition shows a notably different response profile from EVADE and SAFETY BUBBLE, with responses skewed towards disagreement on *Appropriate* in a way that is visually distinct even before statistical testing. For *Appropriate*, the PUSH condition received the lowest ratings ($M = 2.50$), whereas EVADE ($M = 3.58$) and SAFETY BUBBLE ($M = 3.38$) were rated more positively than the BASELINE ($M = 3.17$). For both *Clear Reasoning* ($M = 4.12$) and *Easy to Understand* ($M = 4.00$), the EVADE condition achieved the highest level of agreement among participants. In contrast, *Fair Reaction* responses were more evenly distributed across the conditions, with only minor differences in the observed means: although SAFETY BUBBLE exhibited the lowest mean for this item ($M = 2.96$), the overall response distributions appeared broadly similar across the conditions.

Descriptively, EVADE received the most positive `Perception` ratings

The Friedman test results presented in Table D.1 indicated significant effects of condition for *Appropriate*, *Clear Reasoning*, and *Easy to Understand*, but not for *Fair Reac-*

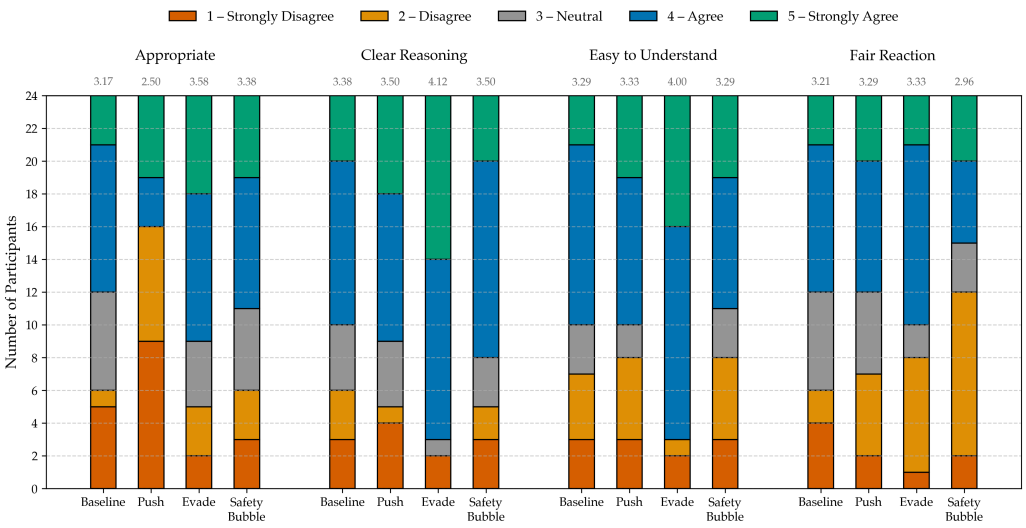


Figure 4.2: Stacked bar charts of Likert-scale responses for the `Perception` section, with mean response scores shown above each bar.

EVADE was rated significantly higher on *Appropriate* than PUSH

tion. As reported in Table D.2, however, the Bonferroni-corrected pairwise comparisons identified a significant difference only for *Appropriate*: participants rated EVADE as significantly more appropriate than PUSH ($p = 0.0095$). No significant pairwise differences were found for *Clear Reasoning* or *Easy to Understand*, nor between any condition and the BASELINE, suggesting that the observed overall effects primarily reflected differences among the countermeasures rather than between the presence and absence of a countermeasure.

Emotional

Six `Emotional` questionnaire items

The `Emotional` questionnaire section assessed participants' emotional responses elicited during the interaction with the virtual avatar. It captured participants' perceived confidence and sense of control, as well as their feelings of safety, stress, discomfort, and social rejection associated with each experimental condition. The questionnaire comprised six items: *Confidence*, *Control*, *Stress*, *Safety*, *Social Rejection*, and *Uncomfortable*.

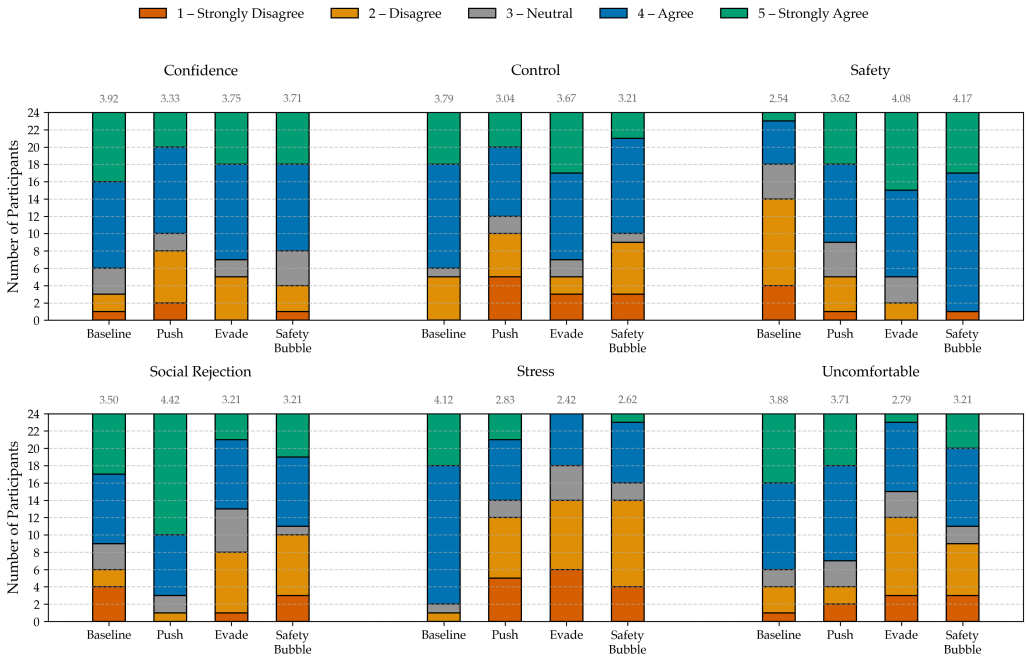


Figure 4.3: Stacked bar charts of Likert-scale responses for the `Emotional` section, with mean response scores shown above each bar.

EVADE and SAFETY BUBBLE yielded the most positive `Emotional` ratings

The Likert-scale response distributions in Figure 4.3 revealed several descriptive differences between the experimental conditions. For both *Confidence* and *Control*, the BASELINE condition received the highest mean ratings ($M = 3.92$ and $M = 3.79$, respectively), whereas PUSH exhibited the lowest mean rating for *Control* ($M = 3.04$). The pattern reversed for *Safety*: BASELINE received the lowest mean rating ($M = 2.54$), while SAFETY BUBBLE ($M = 4.17$) and EVADE ($M = 4.08$) were rated substantially higher. *Stress* responses followed a similar pattern, with BASELINE yielding the highest mean rating ($M = 4.12$) and all countermeasure conditions producing lower ratings, particularly EVADE ($M = 2.42$). Finally, PUSH received the highest mean ratings for *Social Rejection* ($M = 4.42$), whereas EVADE received the lowest rating for *Uncomfortable* ($M = 2.79$).

PUSH elicited the most negative `Emotional` responses

As Table D.1 illustrates, the Friedman tests indicated significant effects of condition for *Control*, *Safety*, *Social Rejec-*

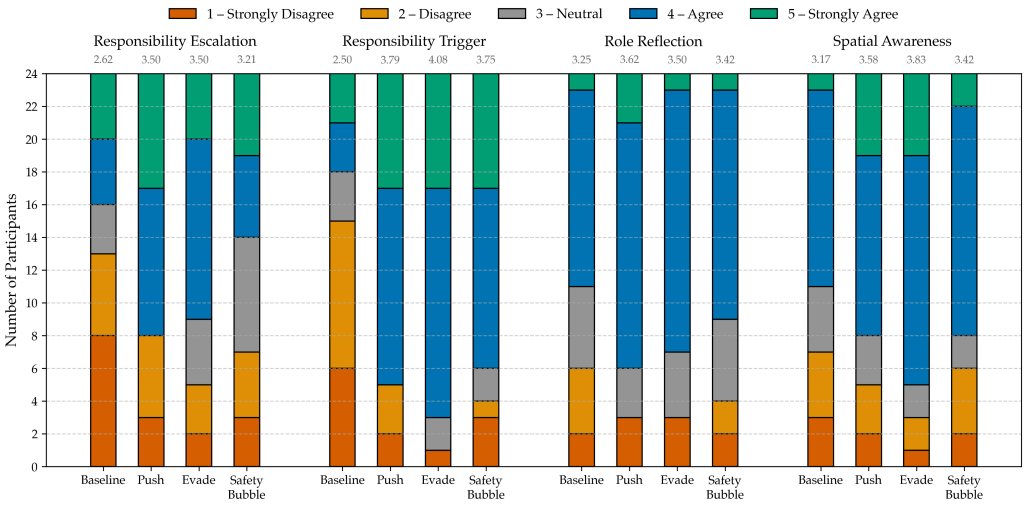


Figure 4.4: Stacked bar charts of Likert-scale responses for the `Self-Reflection` section, with mean response scores shown above each bar.

Countermeasures significantly increased *Safety* and reduced *Stress*

tion, *Stress*, and *Uncomfortable*, but not for *Confidence*. The Bonferroni-corrected pairwise comparisons presented in Table D.3 clarified these effects: BASELINE was associated with significantly lower *Safety* ratings than all three countermeasure conditions ($p \leq 0.0199$) and significantly higher *Stress* ratings ($p \leq 0.0058$). In addition, PUSH elicited significantly higher *Social Rejection* ratings than both SAFETY BUBBLE ($p = 0.0220$) and EVADE ($p = 0.0035$). For *Uncomfortable*, participants also reported significantly lower ratings for EVADE than for both BASELINE ($p = 0.0148$) and PUSH ($p = 0.0483$). Although the Friedman test indicated a significant overall effect for *Control*, the pairwise comparisons did not identify any significant differences.

PUSH elicited significantly greater *Social Rejection*

Self-Reflection

The questionnaire's `Self-Reflection` section assessed participants' reflections on their own role during the interaction after each experimental condition. It focused primarily on whether experiencing the interaction from the invader's perspective influenced participants' sense of responsibility for their behaviour in the virtual environment.

Four `Self-Reflection` questionnaire items

Accordingly, participants were asked whether they felt responsible for triggering or escalating the avatar's response, whether the interaction encouraged them to reflect on their own role, and whether the avatar's response increased their awareness of interpersonal distance and spatial behaviour in VR. The section comprised four items: *Responsibility Escalation*, *Responsibility Trigger*, *Role Reflection*, and *Spatial Awareness*.

Countermeasures increased perceived responsibility relative to the BASELINE

EVADE most strongly increased spatial awareness

The `Self-Reflection` questionnaire revealed a pattern distinct from the previous categories. BASELINE consistently received the lowest mean ratings for both *Responsibility Escalation* ($M = 2.62$) and *Responsibility Trigger* ($M = 2.50$), whereas all three countermeasure conditions exhibited higher levels of agreement; within this broader pattern, EVADE received the highest mean rating for *Responsibility Trigger* ($M = 4.08$), while EVADE and PUSH jointly received the highest mean ratings for *Responsibility Escalation* (both $M = 3.50$). Participants reported broadly comparable levels of agreement for *Role Reflection*, with only minor differences observed between the experimental conditions. *Spatial Awareness* followed a different pattern, with EVADE receiving the highest mean rating ($M = 3.83$), indicating that participants reported the greatest awareness of their spatial behaviour in this condition. Figure 4.4 presents the corresponding Likert-scale response distributions.

All countermeasures significantly increased *Responsibility Trigger*

EVADE significantly increased *Spatial Awareness*

The Friedman test results, presented in Table D.1, indicated significant condition effects for *Responsibility Escalation*, *Responsibility Trigger*, and *Spatial Awareness*, but not for *Role Reflection*. As reported in Table D.4, Bonferroni-corrected pairwise comparisons clarified this pattern: all three countermeasure conditions received significantly higher *Responsibility Trigger* ratings than BASELINE ($p \leq 0.0199$), whereas only EVADE received significantly higher ratings than BASELINE for both *Responsibility Escalation* ($p = 0.0206$) and *Spatial Awareness* ($p = 0.0486$). No significant pairwise differences were observed for *Role Reflection*.

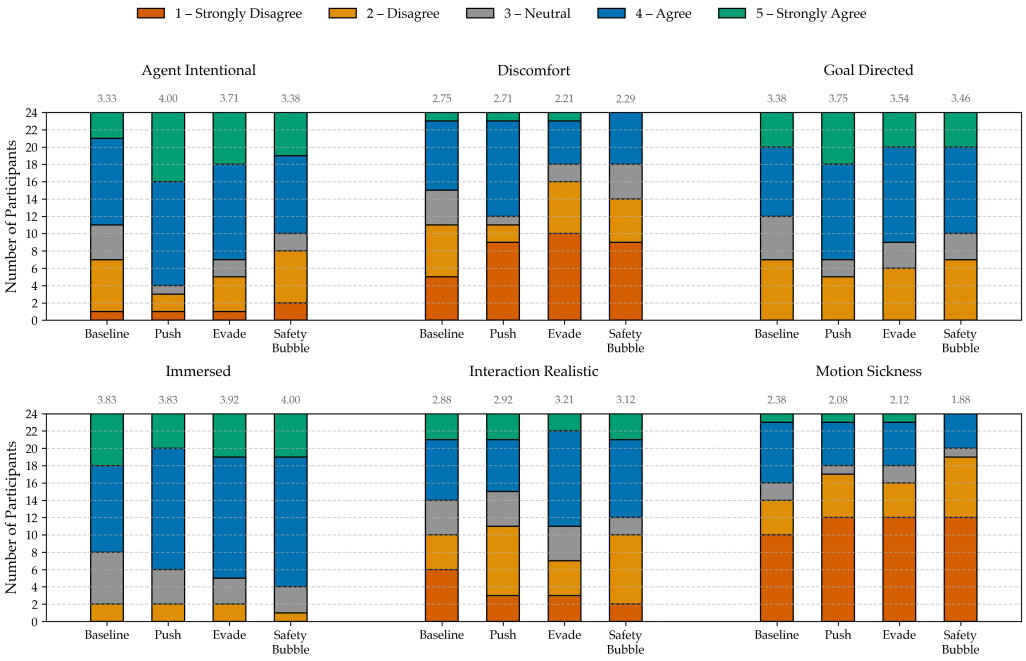


Figure 4.5: Stacked bar charts of Likert-scale responses for the `Realism` section, with mean response scores shown above each bar.

Realism

Six `Realism` questionnaire items

The questionnaire's `Realism` section assessed participants' perceptions of the virtual interaction's realism and plausibility. It measured the extent to which participants felt immersed in the virtual environment, perceived the interaction as realistic, regarded the avatar's behaviour as intentional and goal-directed, and experienced discomfort or motion sickness during the interaction. The section comprised six items: *Agent Intentional*, *Discomfort*, *Goal Directed*, *Immersed*, *Interaction Realistic*, and *Motion Sickness*.

Descriptively, *Discomfort* and *Motion Sickness* remained low

Overall, responses to the `Realism` section remained fairly consistent across the experimental conditions. Participants generally reported low levels of both *Discomfort* and *Motion Sickness*, with the lowest mean ratings observed for EVADE in *Discomfort* ($M = 2.21$) and SAFETY BUBBLE in *Motion Sickness* ($M = 1.88$), whereas ratings for *Agent Intentional*, *Goal Directed*, *Immersed* and *Interaction Realistic* remained

consistent across conditions. Within this broader pattern, PUSH received the highest mean ratings for both *Agent Intentional* ($M = 4.00$) and *Goal Directed* ($M = 3.75$), while responses for *Immersed* and *Interaction Realistic* exhibited only minor differences between conditions. Figure 4.5 presents the corresponding Likert-scale response distributions.

Consistent ratings for *Agent Intentional*, *Goal Directed*, *Immersed*, and *Interaction Realistic*

The Friedman tests indicated significant overall effects of condition for *Agent Intentional*, *Discomfort*, and *Motion Sickness*, as presented in Table D.1; however, the Bonferroni-corrected pairwise comparisons in Table D.5 identified only a single significant difference, with SAFETY BUBBLE receiving lower *Motion Sickness* ratings than BASELINE ($p = 0.0416$). Although significant overall effects were observed for *Agent Intentional* and *Discomfort*, no significant pairwise differences were identified, suggesting that these overall effects reflected more subtle variation across the experimental conditions rather than pronounced differences between specific pairs of conditions. Furthermore, *Goal Directed*, *Immersed*, and *Interaction Realistic* exhibited no significant overall effects.

Overall `Realism` effects reflected subtle differences across conditions

Countermeasure Analysis

The `Countermeasure Analysis` questionnaire section evaluated participants' perceptions of the implemented PSI countermeasures. Specifically, it assessed whether participants regarded each countermeasure as intuitive, real, socially acceptable, justified, predictable, and harsh, as well as whether they would consider reusing it. Because these items were specific to the countermeasures themselves, they were administered only for the SAFETY BUBBLE, EVADE, and PUSH conditions. The questionnaire comprised seven items: *Harsh*, *Intuitive*, *Justified*, *Predictable*, *Realistic*, *Socially Acceptable*, and *Would Reuse*.

Seven `Countermeasure Analysis` questionnaire items

A clear distinction emerged between participants' evaluations of the three countermeasures. PUSH received the highest mean rating for *Harsh* ($M = 4.04$), while also receiving the lowest ratings for *Justified* ($M = 2.38$), *Predictable* ($M = 2.25$), *Socially Acceptable* ($M = 2.12$), and *Would*

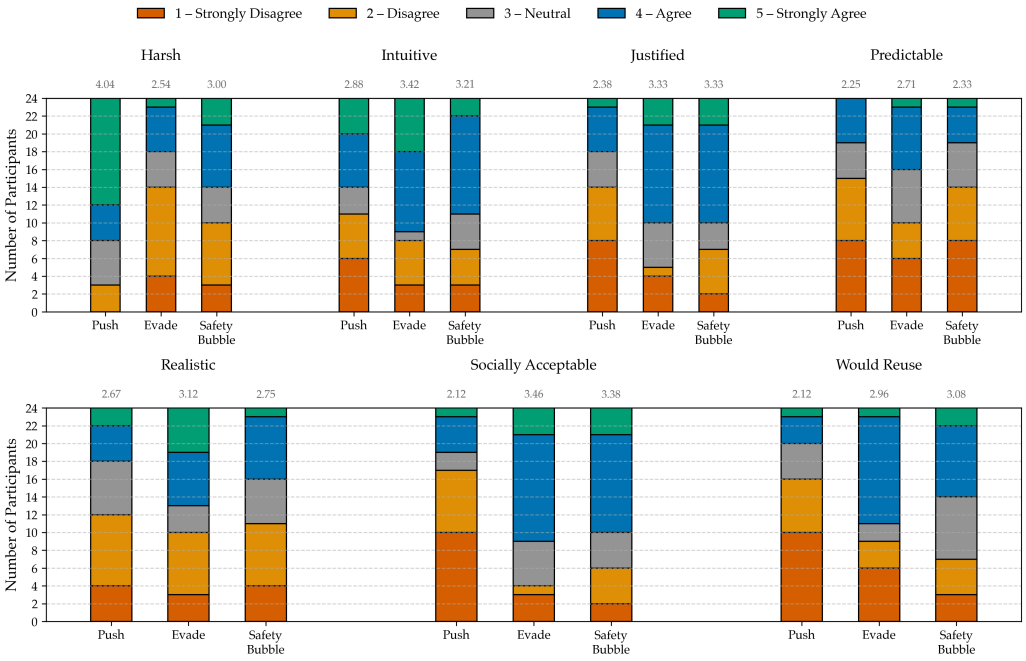


Figure 4.6: Stacked bar charts of Likert-scale responses for the `Countermeasure Analysis` section, with mean response scores shown above each bar.

Descriptively, PUSH was evaluated markedly differently from EVADE and SAFETY BUBBLE

Reuse ($M = 2.12$). By contrast, EVADE and SAFETY BUBBLE were evaluated more favourably across most items: EVADE received the highest mean ratings for *Intuitive* ($M = 3.42$), *Realistic* ($M = 3.12$), and *Socially Acceptable* ($M = 3.46$), whereas SAFETY BUBBLE received the highest rating for *Would Reuse* ($M = 3.08$), and both countermeasures received identical mean ratings for *Justified* ($M = 3.33$). Figure 4.6 provides an overview of the corresponding Likert-scale response distributions.

PUSH differed significantly from both other countermeasures

As Table D.1 illustrates, the Friedman tests indicated significant overall effects of condition for *Harsh*, *Justified*, *Socially Acceptable*, and *Would Reuse*, whereas *Intuitive*, *Predictable*, and *Realistic* did not differ significantly between countermeasures. The Bonferroni-corrected pairwise comparisons in Table D.6 indicated a consistent pattern: PUSH was perceived as significantly more *Harsh* than both SAFETY BUBBLE ($p = 0.0106$) and EVADE ($p = 0.0025$) and participants also rated PUSH as significantly less *Justified*, less *Socially*

Acceptable, and less likely to be *Reused* than both SAFETY BUBBLE ($p = 0.0076$, $p = 0.0123$, and $p = 0.0347$, respectively) and EVADE ($p = 0.0096$, $p = 0.0033$, and $p = 0.0129$, respectively). No significant differences were observed between the SAFETY BUBBLE and EVADE countermeasures for any questionnaire item.

4.1.2 Countermeasure Ranking

In addition to the condition-specific questionnaire responses, participants completed a ranking task that allowed direct comparison of the three active countermeasures across seven evaluation criteria, providing a preference-based complement to the Likert-scale data. The assigned rankings used an Olympic medal system across seven criteria, namely `Intuitiveness`, `Least Physical Demand`, `Least Stress Caused`, `Perceived Safety`, `Realism`, `Sense of Control`, and `Social Acceptability`. For statistical analysis, the rankings were converted into numerical values, with 1 representing the most preferred countermeasure and 3 the least preferred.

Countermeasure ranking across seven evaluation criteria

Figure 4.7 presents participants' mean rankings for the three countermeasures across the seven evaluation criteria, with lower values indicating stronger preference. Overall, SAFETY BUBBLE and EVADE were consistently ranked more favourably than PUSH: SAFETY BUBBLE achieved the most favourable mean rankings for `Least Physical Demand` ($M = 1.46$), `Least Stress Caused` ($M = 1.62$), and `Perceived Safety` ($M = 1.50$), whereas EVADE achieved the most favourable rankings for `Intuitiveness` ($M = 1.58$), `Realism` ($M = 1.71$), `Sense of Control` ($M = 1.62$), and `Social Acceptability` ($M = 1.54$). By contrast, PUSH consistently received the least favourable mean rankings across most evaluation criteria, particularly for `Least Physical Demand` ($M = 2.96$), `Perceived Safety` ($M = 2.62$), `Sense of Control` ($M = 2.54$), and `Social Acceptability` ($M = 2.71$). As Figure 4.7 illustrates, the Olympic medal colour coding mirrors these findings: PUSH is assigned the bronze colour across most criteria, indicating the least favourable rankings.

Descriptively, SAFETY BUBBLE and EVADE were consistently preferred over PUSH



Figure 4.7: Mean participant rankings of the three PSI countermeasures across the evaluated criteria in Study 1, with colours indicating the ranking order.

PUSH differed significantly from both SAFETY BUBBLE and EVADE across multiple criteria

As presented in Table D.7, the Friedman tests revealed significant differences among the countermeasures for `Least Physical Demand`, `Least Stress Caused`, `Perceived Safety`, `Sense of Control`, and `Social Acceptability`, whereas `Intuitiveness` or `Realism` did not differ significantly. The Bonferroni-corrected pairwise comparisons in Table D.8 exhibited a consistent pattern: SAFETY BUBBLE and EVADE did not differ for any ranking criterion, while PUSH was ranked significantly less favourably than both SAFETY BUBBLE and EVADE for `Least Physical Demand`, `Least Stress Caused`, `Sense of Control`, and `Social Acceptability`. For `Perceived Safety`, only the comparison between SAFETY BUBBLE and PUSH reached statistical significance ($p = 0.0011$), whereas the difference between EVADE and PUSH was not significant after Bonferroni correction ($p = 0.0583$).

4.1.3 Qualitative Findings

Reflexive thematic analysis followed Braun et al. [2019]

In addition to the quantitative measures, participants could provide optional comments after each experimental condition and at the end of the study. We imported these comments into *MAXQDA*[1] and analysed them using the six-phase reflexive thematic analysis framework proposed by Braun et al. [2019]. The analysis aimed to identify recurring patterns in participants' experiences that comple-

[1] `https://www.maxqda.com/de/` [Accessed: May 2026]

mented the quantitative findings and provided additional context for interpreting the results. Although the same analytical framework was applied to both studies, the qualitative data in Study 1 consisted of brief optional comments rather than extended interview responses, and the resulting themes should therefore be understood as contextualising the quantitative findings rather than providing independent qualitative depth.

51 codes were generated across four themes

The thematic analysis yielded four overarching themes comprising 51 codes. Table D.9 presents the final codebook, organised by theme and the participant IDs associated with each code. To support transparency and reproducibility, the accompanying Git repository includes a digital copy of the MAXQDA project and the complete codebook. The following sections present the identified themes.

Attitudes Towards Personal Space in VR

Contrasting views on personal space in VR

Participants expressed differing attitudes towards the relevance of personal space in virtual environments. While a minority of participants questioned whether interpersonal distance norms applied in virtual environments at all, the majority reported that experiencing the countermeasures increased their awareness of personal space and its social significance. This diversity of perspectives indicates that participants did not share a common understanding of personal-space expectations in virtual environments. One participant, for example, questioned the need for personal space altogether:

> *"In the virtual world, I personally see no reason to maintain personal space."*
>
> *—Participant U09G (translated from German)*

Emotional and Behavioural Impact of Countermeasures

Countermeasures prompted self-reflection, emotional responses, and appropriateness judgements

Participants described a range of emotional and behavioural responses to the implemented countermeasures, particularly the PUSH condition. Several participants perceived it as overly aggressive and reported discomfort or a reduced sense of control, whereas others reflected on both the appropriateness of the avatar's response and their own contribution to the interaction. One participant, for example, questioned whether the escalation was justified while simultaneously acknowledging their own behaviour:

> *"Violence is never the solution, not even in corridor conflicts. That's why I felt slightly less responsible, because the escalation was the other person's decision, even though my behaviour wasn't nice either."*
>
> *—Participant 124B (translated from German)*

Interpretation of Countermeasure Feedback

Perceptions of auditory and visual feedback

Participants generally interpreted the visual and auditory feedback as an effective means of communicating PSI, though they also identified opportunities to improve how the countermeasures conveyed this information, particularly by making the feedback more gradual and intuitive. One participant, for example, highlighted the role of the auditory feedback in clearly signalling that another user's personal space had been violated:

> *"The freezing noise made it clear that you are invading someone's personal space."*
>
> *—Participant L1K4*

Beyond recognising the purpose of the feedback, several participants proposed refinements to improve its presentation; a recurring suggestion was to introduce the SAFETY BUBBLE more gradually as interpersonal distance decreased, allowing users to anticipate the activation of the countermeasure more naturally:

Participants suggested more gradual and intuitive feedback

> *"Make the bubble appear in a gradient, not suddenly. The bubble should start showing with low translucency as people get closer."*
>
> *—Participant MAD2*

Perceived Realism and Naturalness

Participants evaluated the realism of the implemented countermeasures by comparing them with expected social behaviour in everyday interactions. Within this frame, EVADE was most frequently perceived as the most natural and believable response to a PSI, whereas the SAFETY BUBBLE was often regarded as a more artificial form of intervention. One participant described EVADE as follows:

Realism judged against expected social behaviour

> *"This interaction was the only one that felt truly realistic compared to the others because it showed a relatively clear action by the avatar."*
>
> *—Participant 875X*
> *(translated from German)*

4.1.4 Skin Conductance Analysis

Skin conductance analysis assessed participants' physiological arousal in response to the experimental conditions. The analysis focused on the tonic component of the EDA signal, which reflects sustained changes in physiological arousal over time. Figure 4.8 illustrates the average tonic EDA over the 14 s period following countermeasure activation; the vertical dashed line marks the activation of the

Physiological arousal assessed using tonic skin conductance

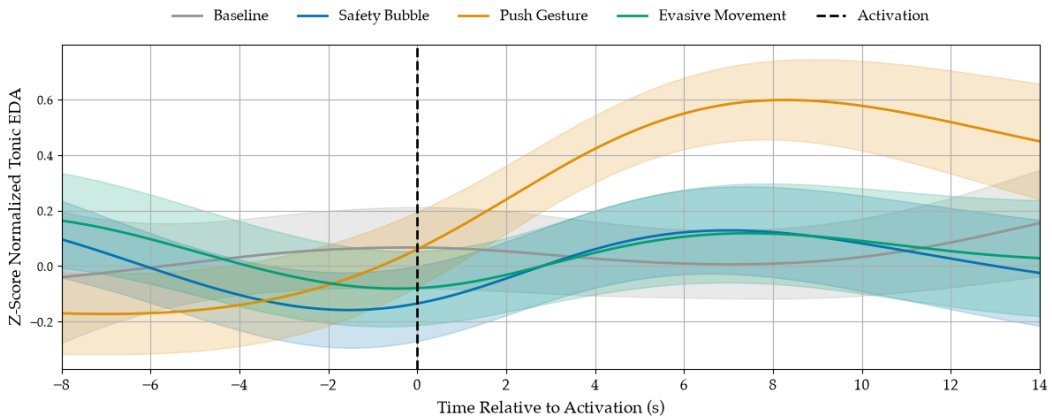


Figure 4.8: Average tonic EDA in Study 1 relative to countermeasure activation, with shaded areas indicating the standard error of the mean.

countermeasure, whereas the shaded regions represent the standard error of the mean.

Descriptively, PUSH elicited the greatest tonic EDA response

Descriptively, PUSH exhibited the largest increase in tonic EDA after activation, reaching its maximum approximately 8 s after the countermeasure was triggered; SAFETY BUBBLE and EVADE displayed smaller increases and followed broadly comparable temporal trajectories, whereas BASELINE remained relatively stable throughout the observation period. Nevertheless, the substantial overlap among the standard-error bands indicated considerable inter-participant variability.

No significant differences in mean or peak tonic EDA

Friedman tests were used to compare the mean and peak tonic EDA across the three countermeasure conditions. Although PUSH exhibited the highest mean tonic EDA change ($M = 0.431$), followed by SAFETY BUBBLE ($M = 0.189$) and EVADE ($M = 0.132$), the tests indicated no statistically significant differences between the countermeasures ($\chi^2 = 0.5833$, $p = 0.7470$). Peak tonic EDA followed the same descriptive pattern, with PUSH again exhibiting the highest mean peak response ($M = 0.959$), followed by EVADE ($M = 0.777$) and SAFETY BUBBLE ($M = 0.604$), but the effect of the condition was not statistically significant ($\chi^2 = 3.5833$, $p = 0.1667$). Overall, the physiological measurements suggested a tendency towards greater sustained physiological arousal during PUSH; however, substantial

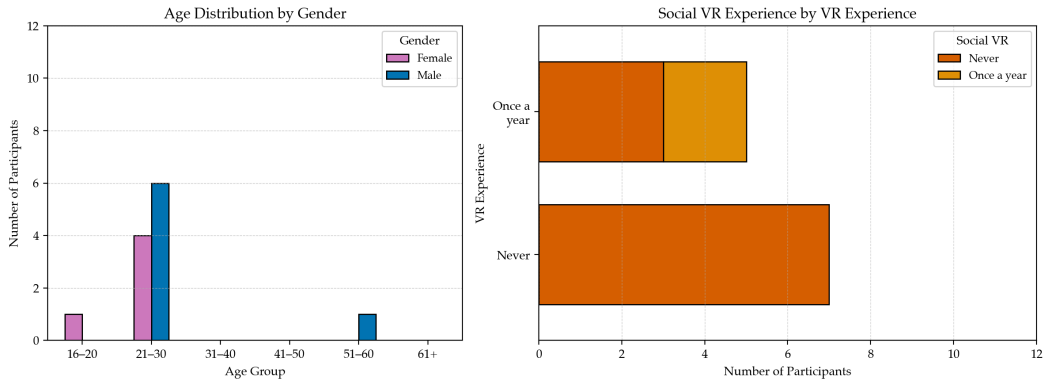


Figure 4.9: Study 2 participant demographics, including age and gender distribution and prior VR and social VR experience.

inter-participant variability accompanied these descriptive differences, and these differences did not reach statistical significance. Table D.10 provides the descriptive statistics for the mean and peak tonic EDA analyses.

4.2 Study 2 Results

The results of Study 2 begin with an overview of participant demographics and then provide an overview of the qualitative findings, organised around four themes derived from the thematic analysis.

Study 2 participant demographics

Study 2 involved 12 participants aged 20 to 57 years (M = 26.75, SD = 9.78), with a median age of 24.5 years. The sample comprised seven male and five female participants; most were university students from technical disciplines, while a small number worked in computing-related fields. Prior experience with immersive technologies was generally limited: most participants reported little or no VR experience, and only two had previously used social VR. As Figure 4.9 shows, the Study 2 sample was similarly limited in social VR experience to Study 1, with only two participants reporting prior use of social VR: a shared characteristic across both studies that is relevant to how the findings generalise to a broader population.

117 initial codes refined into four themes

Following the demographic overview, the interview recordings were transcribed and imported into *MAXQDA* for qualitative analysis. We then applied the same analytic procedure used in Study 1, following the six-phase framework proposed by Braun et al. [2019]. This process generated 117 initial codes, which were subsequently refined into four overarching themes comprising 11 sub-themes. Table D.11 presents the final codebook, and the accompanying Git repository provides the complete codebook synthesis and *MAXQDA* project. The following sections present the identified themes:

4.2.1 Negotiating Personal Space Through Social Communication

Personal space regulation as a collaborative social process

Participants consistently described personal space regulation as a collaborative social process rather than a purely technical problem. Across the interviews, they emphasised that personal space boundaries should be communicated in ways that were intuitive, transparent, and respectful of user autonomy; effective personal space negotiation, in their accounts, depended not only on the implemented countermeasures but also on how users communicated and responded to one another.

Communicating the Countermeasure

Feedback should be intuitive, predictable, and familiar

Participants generally appreciated receiving feedback when they entered another person's personal space, but they emphasised that such feedback should be intuitive, predictable, and based on familiar interaction paradigms. Although they usually understood the purpose of the countermeasures, several participants reported that the feedback occurred too abruptly, making it difficult to anticipate when the reaction would be triggered; familiar techniques, such as controller vibration, were therefore perceived as more natural ways of communicating potential PSIs.

"In my mental model, I've crashed into something, so the controller vibrates. That makes sense to me."

—Participant 1LBN

Earlier warnings could improve anticipation

Several participants also suggested that earlier warning cues would make the countermeasures easier to understand and anticipate:

"The reactions sometimes felt sudden because there was no warning beforehand."

—Participant I0X1

Negotiating Personal Space

Verbal and non-verbal communication supported personal space negotiation

Participants also viewed communication as essential to negotiating personal space in virtual environments. Rather than relying solely on automated countermeasures, they suggested that avatars should communicate their intentions through verbal and non-verbal cues, enabling both users to recognise and address PSIs before stronger interventions became necessary.

"Even just making eye contact, smiling, or using some kind of body language would help the invadee feel less threatened."

—Participant P081

In situations where maintaining personal space was not always possible, such as in narrow passages or crowded environments, participants emphasised the value of direct verbal communication:

"If there's a narrow passage and one person wants to get through, the two people could simply communicate so that one of them moves aside."

—Participant Z2T1

Fairness and User Agency

Participants emphasised preserving user autonomy

Participants consistently emphasised that PSI countermeasures should preserve user autonomy: rather than automatically restricting movement, they preferred interventions that informed users about boundary violations while still allowing them to regulate their own behaviour, especially because PSIs are not always intentional and may result from limited awareness or environmental constraints.

4.2.2 Designing Effective PSI Countermeasures

Design recommendations for future PSI countermeasures

Participants frequently moved beyond evaluating the implemented countermeasures to propose recommendations for improving future PSI countermeasures. Rather than favouring a single solution, they emphasised designs that were intuitive, adaptable, and minimally intrusive, while also considering how systems should communicate boundaries, deliver feedback, and accommodate different users and interaction contexts.

Boundary and Warning Design

Participants advocated visible personal space boundaries

Participants frequently proposed redesigning personal space boundaries so that users could perceive them before a violation occurred. Rather than relying on a single activation threshold, many suggested visible boundary representations and gradual visual cues that would communicate increasing proximity before stronger countermeasures became necessary.

> *"Even if the invader can simply see the circumference on the ground, they would know where the boundary is and could avoid crossing it."*
>
> *—Participant J91B*

Progressive visual cues for boundary awareness

To make activation feel less abrupt, participants also proposed progressive visual indicators, such as changes in colour or transparency, to provide earlier boundary warnings as they approached another person's personal space.

> *"Maybe it could even change colour from yellow to red the closer you get."*
>
> *—Participant C461*

Multimodal Sensory Feedback

Preference for multimodal personal space feedback

Participants frequently discussed complementing visual feedback with additional sensory modalities, particularly haptic and auditory cues. Many viewed controller vibration as a natural way to reinforce proximity awareness, whereas others questioned whether continuous sensory feedback would always enhance the experience, suggesting that it could become distracting during social interactions.

> *"As for audio or haptic cues, I think they could become a little distracting."*
>
> *—Participant Q0P1*

Alternative Countermeasure Concepts

Suggestions extended beyond the evaluated countermeasures

Participants proposed several concepts that extend beyond the countermeasures evaluated in the study. Their suggestions ranged from avatar-shaped personal-space boundaries and system-assisted movement redirection to friendship-based permissions and blocking or warning mechanisms modelled on existing social VR platforms. Together, these suggestions indicate that participants viewed personal space support as extending beyond the three countermeasures investigated in this study.

Adaptive Countermeasure Behaviour

PSI countermeasures should adapt to users and context

Participants suggested that PSI countermeasures should adapt to different users and interaction contexts rather than relying on a single fixed response. Several proposed allowing users to customise their preferred interpersonal distance, while others suggested that countermeasures could dynamically respond to environmental constraints or the relationship between users. Rather than applying the same intervention in every situation, participants favoured systems that responded proportionally to the context and supported users in navigating social interactions with minimal disruption. One participant, for example, proposed subtly redirecting the invader's movement to avoid PSIs without interrupting the interaction:

> *"Even though you're technically walking towards the other person, the system could slightly shift your movement sideways without you noticing, so that, from the invadee's perspective, you simply slide around the Bubble instead of entering it."*
>
> *—Participant C461*

4.2.3 Experiences and Evaluation of Countermeasures

Participants' evaluation of the implemented countermeasures

Participants reflected on the implemented countermeasures after interacting with them from both the invader and invadee perspectives. Across the interviews, they evaluated each intervention's realism, effectiveness, emotional impact, and overall suitability, highlighting the strengths and limitations of the different approaches.

Perceived Realism

Participants frequently evaluated the countermeasures by comparing them with expected real-world interpersonal behaviour. Across the interviews, EVADE was consistently perceived as the most realistic response because stepping aside or backwards reflected familiar social behaviour, whereas SAFETY BUBBLE was often described as more artificial, and PUSH was frequently interpreted as resembling a slap. Several participants therefore suggested replacing PUSH with a gentler one-handed push that more closely resembled everyday interpersonal interactions.

Participants evaluated countermeasures against real-world social behaviour

Perceived Effectiveness

Participants evaluated the countermeasures according to how effectively they prevented PSIs. Stronger interventions were generally considered more effective at stopping the invader, though participants often viewed them as disproportionate when PSIs were unintentional; as a result, effectiveness alone did not define perceived appropriateness.

Trade-off between effectiveness and proportionality

> *"I also think the Push countermeasure is still necessary because some people simply won't behave the way we'd like them to."*
>
> *—Participant P081*

By contrast, less intrusive countermeasures such as EVADE were regarded as more socially appropriate, though some participants considered them less able to discourage continued approach behaviour.

Appropriateness did not always ensure effectiveness

> *"With Evade, I knew the other person had moved away, but if there hadn't been a physical collision or stop in VR, I probably would have continued moving forwards anyway."*
>
> *—Participant 7M8W*

Emotional and Behavioural Responses

Countermeasures promoted awareness and self-reflection

Participants described a range of emotional and behavioural responses to the implemented countermeasures. Many reported becoming more aware of both their own behaviour and the other users' personal space, while also describing surprise, discomfort, or frustration when interventions were perceived as abrupt or disproportionate.

EVADE and PUSH evoked contrasting emotional responses

The movement-based countermeasures, EVADE and PUSH, evoked noticeably different experiences: EVADE was commonly described as a subtle cue that encouraged participants to adjust their behaviour, whereas PUSH more often interrupted the interaction and produced a stronger emotional response.

Countermeasure Preference

SAFETY BUBBLE was the most frequently preferred countermeasure

Participants expressed diverse preferences for the implemented countermeasures, reflecting different priorities regarding realism, effectiveness, and social appropriateness. Overall, SAFETY BUBBLE emerged as the most frequently preferred countermeasure because it prevented PSIs without creating direct confrontation.

> *"Definitely the Bubble. The reason is that it solves the problem without creating confrontation between people."*
>
> *—Participant AI12*

No single countermeasure suited all situations

Although participants widely regarded EVADE as the most natural countermeasure and considered PUSH appropriate in situations requiring a stronger intervention, they generally viewed the three approaches as suited to different circumstances rather than as options with a single best solution. Many therefore favoured combining multiple countermeasures that could be adapted to different situations and levels of PSIs.

4.2.4 Contextual Factors Influencing Personal Space in Social VR

Personal space was perceived as context-dependent

Participants consistently described personal space as context-dependent rather than by a fixed interpersonal distance. In their accounts, environmental constraints, social relationships, and perceived user intentions influenced both the acceptability of PSIs and the suitability of different countermeasures.

Several participants identified narrow corridors and crowded environments as situations in which avoiding PSIs would often be tough or impossible; in these contexts, they argued that countermeasures should account for the environmental restraints when deciding how to respond.

> *"I will inevitably have to enter their personal space at some point in order to pass them."*
>
> *—Participant C461*

Personal space depended on the relationship between users

Participants also emphasised that acceptable interpersonal distance depended on the social relationship between users. Several noted that they would respond differently depending on whether the other user was a stranger, acquaintance, or friend; others suggested that avatar characteristics could similarly influence how comfortable they felt during the interaction.

> *"I think I would have felt more comfortable with a female avatar."*
>
> *—Participant Q0P1*

Taken together, the results of both studies suggest that invaders consistently preferred countermeasures that communicated personal space boundaries before imposing restrictions, valued interventions that resembled familiar social behaviour, and viewed stronger interventions as appropriate only when earlier communication had failed. These findings are examined in depth in the following chapter.

Chapter 5

Evaluation

This chapter evaluates and discusses the findings reported in Chapter 4. The results of both studies converge in demonstrating that invaders consistently preferred countermeasures that communicated personal space boundaries before imposing direct restrictions, a pattern that the following discussion interprets in relation to the research questions and existing literature. The chapter is divided into three sections: the first examines invaders' responses to the countermeasures under investigation; the second explores the implications for designing future countermeasures; and the final section outlines the limitations of the conducted studies.

5.1 Understanding Invaders' Responses to PSI Countermeasures

The results of both studies converge in revealing that invaders did not reject PSI countermeasures: they responded differently depending on how clearly and fairly each countermeasure communicated the personal space boundary.

Communication shaped acceptance of PSI countermeasures

RQ1 How do invaders respond to countermeasures, and which types of countermeasures do they perceive as most acceptable or preferable?

Together, these findings address *RQ1* and are discussed in the following subsections:

Preventive Communication of Personal Space Boundaries

Explicit communication improved countermeasure acceptance

The two studies clearly indicated that participants consistently preferred the countermeasures that defined personal space boundaries before imposing direct movement restrictions. Participants valued interventions that preserved their sense of agency, allowing them to recognise and voluntarily correct an impending PSI rather than having their movement automatically restricted. These findings indicate that explicit communication is important for the acceptance of PSI countermeasures.

Participants rated PUSH less favourably than the other countermeasures

The same preference for communicative over coercive countermeasures was apparent in Study 1's quantitative results. The `Countermeasure Analysis` indicated that the SAFETY BUBBLE and EVADE countermeasures were much more socially acceptable and justified than the PUSH countermeasure, and participants were significantly more ready to reuse them. By comparison, participants judged the PUSH countermeasure to be far more severe than the other two options. The ranking task also supported this pattern: participants consistently associated the SAFETY BUBBLE with higher perceived safety, lower stress, and lower physical demand, indicating that they preferred countermeasures that communicated personal space boundaries without resorting to forceful intervention.

Physiological evidence suggested greater arousal for PUSH

The physiological findings neither confirmed nor contradicted these subjective evaluations. Although neither the mean nor peak tonic skin conductance analyses revealed statistically significant differences among the countermeasures, the PUSH condition consistently produced the largest increase following activation. These descriptive trends should be interpreted with caution; nevertheless, they suggest that abrupt physical interventions may evoke greater emotional arousal than countermeasures that first communicate interpersonal boundaries before intervening.

Preventive countermeasures enabled voluntary self-correction

The qualitative findings further clarify this preference for preventive countermeasures. Rather than viewing the SAFETY BUBBLE as a barrier that prevented movement, participants frequently described it as a warning: it informed them that they were approaching another person's personal space. Participants considered this distinction important because it allowed invaders to recognise a potential PSI and voluntarily adjust their behaviour before a stronger intervention became necessary. Across both studies, they repeatedly associated this opportunity for self-correction with fairness and respect for both interaction partners, suggesting that they valued clear communication more highly than immediate behavioural restriction.

Participants preferred gradual communication of personal space boundaries

These findings are consistent with, and extend, prior work on personal space regulation in social VR. Nassiri et al. [2009] suggested that the personal space bubble should remain hidden until another user attempts to enter it, at which point the border should become visible to explain why further movement is blocked. Participants in the present work similarly appreciated inconspicuous personal space bubbles, though several also objected to the sudden halt in movement after reaching the border. Instead, they proposed incrementally increasing visual, auditory, or tactile cues as users approached another person's personal space, allowing them to identify and avoid a potential PSI before physical action became necessary. Freeman and Acena [2021] similarly found that users appreciated personal space bubbles as a proactive way of avoiding unwelcome contacts. Blehm [2025] also found that preventive countermeasures enhanced the invadee's experiences compared to having no protection. The present work extends these findings: invaders also value preventive countermeasures when they transparently expressed the personal space boundaries and permitted voluntary behavioural adjustments.

Findings extend prior work to the invader's perspective

Socially Meaningful Communication of Personal Space Boundaries

Socially meaningful communication shaped countermeasure acceptance

Although participants consistently preferred preventive countermeasures, prevention alone did not ensure acceptance. Across both studies, participants also evaluated how personal space boundaries were communicated, expressing a clear preference for interactions that resembled familiar social behaviour rather than abrupt, system-enforced responses. These findings suggest that socially meaningful communication is a key factor in the acceptance of PSI countermeasures.

EVADE was perceived as the most realistic and intuitive

This difference also appeared in Study 1's quantitative results. In the questionnaire's `Countermeasure Analysis` section, participants rated SAFETY BUBBLE and EVADE similarly positively overall. Within this overall positive evaluation, however, they perceived EVADE as more realistic, intuitive, and socially acceptable than the other conditions. The rankings further supported this interpretation, with EVADE ranked as the most realistic and intuitive countermeasure.

Socially meaningful countermeasures encouraged self-awareness

Apart from these evaluations, EVADE appeared to promote greater self-reflection. Participants reported higher levels of spatial awareness and more frequent reflection on their own role in the encounter. This suggests that the avatar's behaviour prompted them to consider how their own actions contributed to the developing PSI. In summary, these results suggest that socially meaningful countermeasures not only express interpersonal borders but may also motivate users to become more aware of their own behaviour.

Participants interpreted EVADE as natural social behaviour

The qualitative results help explain why participants responded more favourably to EVADE. Rather than interpreting the avatar's evasive movement as a fixed system response, many participants interpreted it as a familiar interpersonal behaviour that they would expect from another person in a comparable real-world situation. In most cases, they understood the gesture as the avatar creating personal space without escalating the situation, making the interaction more understandable and socially acceptable. Rather than merely observing the avatar's action, partic-

ipants often attempted to infer its intentions from its behaviour, characterising the movement as a courteous attempt to maintain personal space rather than as a random system response.

Participants advocated multiple non-verbal social cues

Across both studies, however, participants emphasised that movement alone was insufficient to fully communicate the invadee's intentions; they proposed that avatar behaviour should be augmented with non-verbal social cues such as gaze, posture, and gesture. This observation shows that participants expected personal space limits to be communicated through a combination of social cues, rather than through explicit system interventions alone, and has direct implications for the design of socially enriched countermeasures, as discussed in the following section.

The findings support the Plausibility Illusion

Countermeasures should communicate socially meaningful intentions

These findings are also consistent with broader work within social VR research. Slater's [2009] account of the Plausibility Illusion suggests that people react more naturally to virtual characters that behave in socially plausible ways. The current results are consistent with this proposition, as participants repeatedly characterised the evasive movement as a socially intentional response rather than as a system-defined action. Similarly, Wang et al. [2025] found that users appreciated negotiation-based teleportation methods, which significantly improved privacy protection and reduced anxiety associated with unwanted proximity. Although that interaction differs from the one examined here, both studies imply that interventions are more acceptable when they preserve the social nature of the interaction. Together, these findings suggest that effective PSI countermeasures should not only govern interpersonal distance but also express another user's intentions in a socially meaningful manner.

Context-Dependent Acceptance of Strong Interventions

Stronger interventions were accepted when proportionate

This preference for preventive and socially meaningful responses should not be mistaken for a rejection of stronger interventions. In general, participants distinguished between interventions that seemed unduly forceful and those they considered appropriate for the situation. They evaluated the appropriateness of the PUSH countermeasure not in principle, but according to whether the response seemed proportionate to the unfolding PSI.

PUSH was understood but perceived as disproportionate

This pattern also emerged in Study 1's quantitative data. Participants rated the PUSH countermeasure as significantly harsher, less justified, and less socially acceptable than the SAFETY BUBBLE and EVADE countermeasures, and they were significantly less willing to use it themselves. At the same time, they consistently rated all three countermeasures highly for *Clear Reasoning*, *Easy to Understand*, and *Agent Intentional*. Collectively, these results indicate that participants understood the aim of the PUSH countermeasure but perceived it as disproportionate to the scenario provided. Although the physiological analyses did not reveal statistically significant differences, the PUSH condition also consistently produced the largest increase in tonic skin conductance following activation. The considerably higher ratings of EVADE for *Appropriate* point in the same direction: participants regarded less intrusive behavioural responses as a more suitable way to address PSI.

PUSH was viewed as a final-stage intervention

The qualitative findings further clarify why participants evaluated the PUSH countermeasure less favourably in the experimental scenario. Rather than rejecting forceful interventions altogether, participants repeatedly described them as appropriate only when less intrusive countermeasures had failed or when another user deliberately continued to violate the invadee's personal space. Many viewed the PUSH countermeasure as a final stage within a sequence of escalating interventions, rather than as an appropriate initial response to an accidental or first-time PSI.

Repeated or intentional PSIs justified stronger interventions

Participants repeatedly explained that the appropriateness of stronger interventions was situation-dependent. In general, they viewed more aggressive responses as justified when another user repeatedly or deliberately violated personal space, especially if previous attempts to communicate interpersonal boundaries had been ignored. Participants also referred to crowded or spatially constrained environments, where PSI was sometimes unavoidable regardless of intent, a context in which stronger interventions were viewed as disproportionate. Rather than treating more aggressive interventions as inevitably appropriate, they assessed them in regard to the context in which they were used.

Invaders also preferred escalating intervention strategies

Contemporary social VR platforms reflect a similar logic by providing multiple safety mechanisms that allow responses to scale with the severity of an interaction, rather than relying on a single intervention. The present findings extend this narrative by suggesting that invaders likewise conceptualise PSI countermeasures as part of an escalating sequence. Preventive communication was generally preferred as an initial response, whereas stronger interventions were considered appropriate only after earlier attempts to establish interpersonal boundaries had failed or when another user deliberately continued the violation. Collectively, these findings suggest that the acceptability of stronger countermeasures depends less on the countermeasure itself than on whether users perceive it as a proportionate response to the social context.

Together, these findings indicate that invaders did not reject PSI countermeasures as a category; they evaluated them according to three interrelated criteria: whether they communicated boundaries before restricting movement, whether they did so through socially recognisable behaviour, and whether the response was proportionate to the perceived severity of the violation. These observations provide the foundation for the design considerations discussed in the following section.

5.2 Designing Mutually Acceptable Countermeasures

Findings informing the design of future PSI countermeasures

The discussion of the first research question identified several features that influenced participants' acceptance of PSI countermeasures. Building on these findings, the second research question shifts from evaluation to design, considering how future social VR systems can be designed to reduce unintentional PSI while remaining acceptable to both interaction partners.

RQ2 What countermeasures or support mechanisms can be designed to reduce unintentional PSI while remaining mutually acceptable?

Rather than focusing solely on the design of individual countermeasures, the following sections consider how the design of future systems can support all actors involved in a PSI. The proposed design considerations are therefore organised around three complementary perspectives: helping the invadee communicate personal space boundaries, helping the invader recognise and avoid unintentional PSI, and supporting both users through platform-level mechanisms that adapt to the social context.

Invadee-Oriented Countermeasure Design

Invadees should communicate discomfort before intervening

Throughout the interviews, participants repeatedly discussed how existing countermeasures could communicate the invadee's personal space boundaries more efficiently. Rather than proposing entirely new countermeasures, many focused on enriching existing mechanisms so that the invadee's discomfort became visible before stronger interventions were required. Across both studies, participants suggested that the invadee should be able to gradually express the desire for greater interpersonal distance, allowing invaders to recognise these cues and adjust their behaviour before the interaction escalates.

Participants proposed several refinements that would define the invadee's personal space boundaries more clearly. Instead of simply displaying a static visual personal space bubble, many suggested that the representation should change as another person approached, for instance by gradually shifting in colour or opacity. This visual would warn potential invaders of an impending PSI without abruptly interrupting the interaction. Others suggested more spatially specific representations, including clearly defined borders projected onto the floor or avatar-shaped hitboxes that more closely approximated the invadee's avatar and supported more natural movement.

Personal space boundaries should be communicated visually

Participants also suggested adding gaze direction, facial expressions, body posture or subtle gestures to these visual cues, as such behaviours can naturally signal discomfort and the need for greater interpersonal distance. Rather than relying on one single visual indicator, participants favoured multiple complementary cues that could communicate the invadee's personal space boundaries in a more intuitive and socially meaningful way.

Non-verbal social cues should complement visual feedback

Interestingly, participants rarely argued that existing countermeasures themselves should be replaced. Instead, they consistently sought ways to make them easier to perceive and interpret. Their focus, therefore, remained on improving how the invadees communicated their personal space boundaries rather than on introducing entirely new interventions. Many also proposed combining multiple countermeasures and communication cues within the same interaction, so the visual, behavioural, and environmental signals could complement one another before stronger interventions became necessary. Overall, these findings suggest that future PSI countermeasures may benefit less from additional intervention mechanisms than from enabling the invadees to communicate discomfort clearly, naturally, and through a combination of complementary cues.

Existing countermeasures should be refined rather than replaced

Invader-Oriented Support Mechanisms

The previous section considered how countermeasures could better communicate the invadee's personal space boundaries; this section turns to the invader's perspective, examining how systems could better support users before they breach another person's personal space. Many argued that preventing unintentional PSI should not rest solely with the invadee; rather, future systems should help invaders recognise nearby personal space boundaries before a countermeasure becomes necessary. Participants emphasised that many PSIs resulted from limited spatial awareness or uncertainty about the invadee's comfort level. They therefore proposed support mechanisms that would help invaders recognise an impending PSI, interpret the invadee's boundaries, and adjust their behaviour before the interaction escalated.

PSI prevention should not rely solely on the invadee

Participants proposed several mechanisms for increasing invaders' awareness of nearby personal space boundaries: proximity indicators resembling a wireless signal, distance bars that continuously visualised the remaining distance to the invadee's personal space boundary, and progressively increasing auditory feedback, which participants compared to a car's reversing sensors. Others proposed subtle controller vibrations that intensified as interpersonal distance decreased, allowing invaders to perceive an approaching boundary without interrupting the interaction. Collectively, these mechanisms were intended to provide continuous feedback while allowing invaders to remain in control of their own movement.

Participants proposed continuous proximity awareness cues

Participants rarely viewed these mechanisms as additional countermeasures. Instead, they described them as forms of support that would help invaders become more aware of their surroundings and avoid unintentional PSIs altogether. Several participants also emphasised that such feedback should remain gradual and unobtrusive: they often perceived abrupt warning sounds as startling or error-like, with some comparing the implemented sound to an object breaking. They preferred auditory feedback that increased progressively in intensity, again drawing on the compari-

Awareness mechanisms were viewed as support rather than intervention

son with a car's reversing sensors, because this would allow them to anticipate an approaching boundary without disrupting the interaction. Participants expressed similar preferences for haptic feedback, favouring nuanced controller vibrations over systems that physically affected the headset or the user's motion.

In summary, these results suggest that future systems should support invaders through continuous awareness mechanisms that encourage voluntary behavioural adjustment, rather than relying solely on reactive countermeasures. By enabling invaders to recognise the invadee's discomfort and an impending PSI before interpersonal boundaries are crossed, such support mechanisms may reduce unintentional violations, while preserving the invader's sense of agency and the invadee's personal space.

Future systems should support voluntary behavioural adjustment

Platform-Level Personal Space Regulation

Participants' comments extended beyond individual countermeasures and support mechanisms: they repeatedly considered how the platform itself could coordinate personal space regulation. Rather than expecting every interaction to rely on a single predefined countermeasure, many envisioned the platform as an active mediator that could support both interaction partners according to the surrounding social context. Throughout the interviews, participants proposed platform-level mechanisms that would support communication, adapt to different situations, and coordinate personal space regulation in ways that balanced the needs of both the invadee and the invader.

Participants advocated platform-level support for PSI regulation

One recurring suggestion was that future platforms should support communication between users before automatically intervening. Participants repeatedly proposed that platforms could help resolve many instances of unintentional PSI by giving users simple ways to communicate discomfort or intentions, such as through voice communication, predefined messages, or non-verbal interaction cues. Several participants also suggested mechanisms that would encourage users to acknowledge one another or ne-

Participants preferred mutual understanding over automatic intervention

gotiate interpersonal boundaries before the platform activated stronger countermeasures. Overall, they preferred systems that supported mutual understanding and voluntary behavioural adjustment over immediate system-enforced intervention.

Participants advocated perspective-dependent personal space regulation

Participants also recognised that VR enables forms of personal space regulation that are not possible in the physical world. Rather than presenting an identical interaction to both users, several participants suggested that future platforms could tailor the experience to each user's perspective: some envisioned invaders continuing to walk along their intended paths, whereas the invadees would simultaneously perceive those users as moving around a personal space boundary. Participants felt that this kind of perspective-dependent interaction could preserve the invadee's sense of safety without disrupting the invader's experience, thereby minimising the need for more intrusive interventions.

Platforms should be personalised to users, relationships, and context

Participants regularly questioned whether a single personal space policy could be effective in all situations. Many argued that future platforms should consider personal preferences, the relationship between invader and invadee and the social context in which an interaction occurs. For example, they suggested allowing users to adjust the size of their personal space boundaries, adapting countermeasures in crowded settings, or varying the intensity of interventions depending on whether a PSI appeared to be accidental, recurrent, or deliberate. Rather than applying a one-size-fits-all approach, participants envisioned platforms that customised personal space regulation to fit the interaction's specific context.

Mutually acceptable PSI requires support for both interaction partners

In answer to *RQ2*, the findings suggest that mutually acceptable countermeasures should combine invadee-oriented visual and behavioural cues, invader-oriented proximity awareness support, and platform-level adaptive mechanisms that respond to relationship, context, and the severity of the violation. As reducing unintentional PSI requires support for both interaction partners rather than relying on countermeasures alone, Figure 5.1 synthesises participant-inspired design concepts that emerged from the

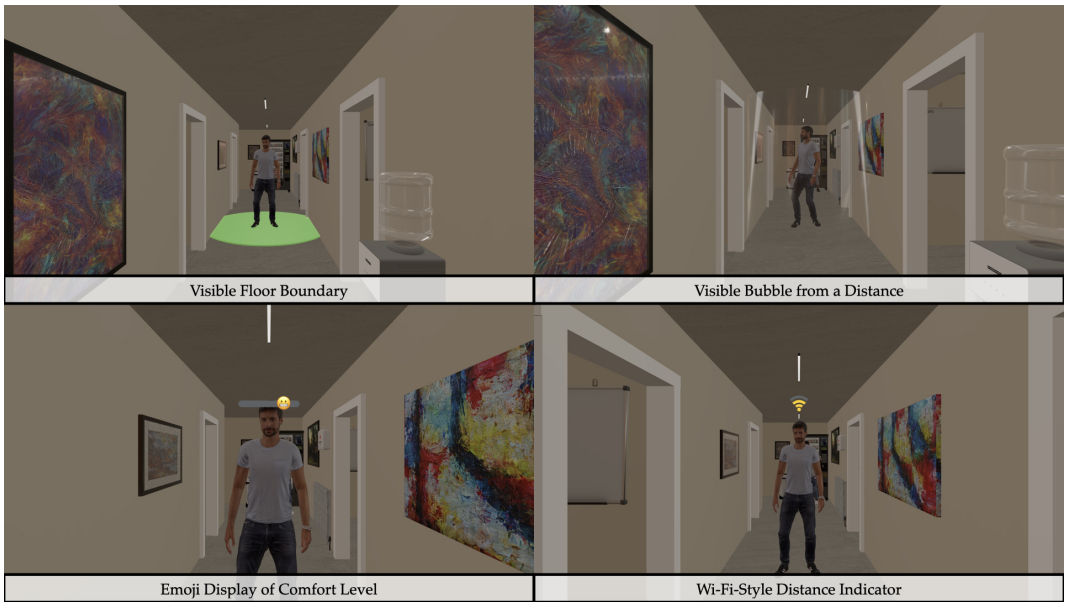


Figure 5.1: Examples of participant-inspired design concepts for mutually acceptable personal space regulation.

interviews and illustrates how these complementary support mechanisms could be realised in future social VR systems. The proposed design considerations are therefore organised around three complementary perspectives: enabling invadees to communicate personal space boundaries, helping invaders recognise and avoid unintentional PSI, and providing platform-level mechanisms that adapt to the surrounding social context.

5.2.1 Emerging Design Considerations

Design considerations derived from the empirical findings

Taken together, the findings discussed point towards a few considerations for designing future PSI countermeasures. We present these considerations as recommendations based on the study results rather than as validated guidelines: they derive from participants' experiences with a fixed set of countermeasures and would benefit from further development and testing through purpose-built designs.

Design Consideration 1: Preventive Boundary Communication

The first consideration concerns the *point at which a countermeasure intervenes*. Participants consistently preferred countermeasures that signalled a boundary to those that restricted movement directly. Accordingly, participants evaluated SAFETY BUBBLE and EVADE more favourably than PUSH for safety, stress, and physical demand, while rating PUSH significantly harsher and less acceptable. In the interviews, the recurring request was not for an entirely different boundary but for one that appeared earlier and more gradually, for example, through a bubble that faded in with proximity, or a warning before movement was restricted. Countermeasures may therefore be more readily accepted when they signal a boundary early enough for invaders to correct their course.

Design Consideration 2: Proportionate countermeasure responses

The second consideration concerns *the strength of the response*. Participants' preference for gentler signals did not amount to a rejection of forceful interventions. They understood PUSH as intentional and well-reasoned; however, they judged it disproportionate as a first response to an accidental intrusion, while several still regarded it as a reasonable last resort after gentler cues had failed. This pattern points towards interventions that scale according to the context, including repetition, crowding, and apparent intent, rather than responding the same way every time. The discomfort some participants reported in the invader role further suggests that systems should not treat an unintentional approach as hostile by default.

Design Consideration 3: Reciprocal Personal Space Support

Finally, our findings suggest a *potential trade-off between acceptability and effectiveness*, as the most acceptable countermeasure was often the least effective. Participants perceived EVADE as natural but easy to ignore; PUSH reliably stopped the approach, but they rejected it as too forceful. Refining a single countermeasure, therefore, seems unlikely to satisfy both objectives simultaneously. One direction for future work is therefore to distribute the response across both users: the invadee could gradually communicate a boundary, while the invader receives support to perceive and respect it, so that forceful intervention becomes a last resort. This discussion presents that direction as a promising avenue rather than a conclusion, since the stud-

ies were not designed to test a reciprocal approach directly.

5.3 Limitations

Although the two studies provide complementary insights, their findings presented in this thesis should be interpreted within the scope of the research design. The studies deliberately prioritised experimental control over ecological validity, enabling direct comparisons of PSI countermeasures under consistent conditions. Accordingly, both studies occurred in a virtual office corridor and used a predefined navigation task; although this strengthened the findings' internal validity, it represents only a limited range of the social situations encountered in contemporary social VR platforms. Moreover, the studies focused exclusively on frontal interactions, even though full immersive social VR enables encounters from all directions, and they employed only controller-based locomotion. Consequently, the reported findings should not be assumed to generalise to other environments, interaction scenarios, or locomotion techniques.

Generalisability is limited to the investigated VR scenario

The two studies provided complementary quantitative and qualitative perspectives, yet both relied on relatively small samples composed predominantly of university students. In addition, most participants reported little or no prior experience with social VR; consequently, the findings should be interpreted within the context of the participant population examined in this thesis. Relatedly, the EDA measurements did not yield significant differences across the countermeasures. Given the descriptive trend and the high inter-participant variability, this may reflect insufficient statistical power; hence, a larger sample size would help establish whether more assertive countermeasures produce higher physiological arousal.

Participant sample was predominantly students with limited social VR experience

The fixed position of the baseline condition presents another limitation. The baseline condition was always presented first so that participants could familiarise themselves with the interaction before experiencing the countermeasures. While this design reduced comparisons with

Fixed baseline order may have introduced an order effect

previously experienced interventions, it may also have introduced an order effect. Participants also believed they were interacting with another user, although the counterpart's behaviour was predetermined; this perspective increased the interaction's plausibility, but it did not capture the spontaneity of genuine multi-user encounters.

Thematic analysis was conducted by a single researcher

Although an established thematic analysis framework was followed and the coding was refined iteratively, the analysis was not subject to independent peer review or inter-rater reliability checking, which represents a limitation of the single-researcher approach within the scope of a master's thesis. To support transparency and traceability of this process, the complete analytic workflow is provided in the accompanying repository, documenting all six phases of the thematic analysis approach of Braun et al. [2019] for the qualitative components of both studies.

Countermeasure and avatar diversity were limited

Finally, this thesis evaluated only three personal space countermeasures, selected as representative examples of preventive, behavioural, and restrictive approaches to personal space regulation rather than an exhaustive set of solutions. Further, both studies used a single invadee avatar. Because avatar characteristics may influence interpersonal distance preferences, the findings should be interpreted within the context of the specific avatar used in this work.

Chapter 6

Summary and Future Work

This chapter summarises the thesis's main findings and contributions. It also outlines potential directions for future research that could extend and build on the present work.

6.1 Summary

Thesis overview and research contribution

Personal space regulation is essential for maintaining comfortable and socially acceptable interactions in social VR. Although numerous countermeasures aim to protect users from PSIs, comparatively little work has examined how these interventions affect the invaders who trigger them. This thesis therefore investigated invaders' responses to existing PSI countermeasures and explored how future social VR systems can reduce unintentional PSIs while remaining acceptable to both interaction partners. The thesis used a mixed-methods approach, combining a controlled quantitative study with an exploratory qualitative study; together, these studies examined participants' experiences with existing countermeasures and derived participant-inspired design implications for future personal space regulation in social VR.

Acceptance depended on clear and proportionate communication

The findings indicate that invaders consistently preferred countermeasures that communicated personal space boundaries before imposing direct restrictions on their movement. Participants perceived the SAFETY BUBBLE and EVADE countermeasures as more appropriate, socially acceptable, and justified than the PUSH countermeasure, while the qualitative findings further revealed that they valued interventions that allowed them to recognise and correct an impending PSI voluntarily. The physiological data, though statistically not significant, showed descriptively higher arousal during the more restrictive PUSH condition. Collectively, the results suggest that the acceptability of PSI countermeasures depends less on whether they intervene than on how clearly and proportionately they communicate the invadee's personal space boundaries.

Design considerations emphasised communication and shared support

Beyond evaluating existing countermeasures, the thesis identified several design considerations for future personal space regulation in social VR. Rather than proposing entirely new intervention mechanisms, participants consistently emphasised the need to improve communication between interaction partners. They envisioned future systems in which invadees could communicate personal space boundaries more naturally, invaders would receive support that increased their spatial awareness, and platforms would coordinate these mechanisms according to the surrounding social context. Together, these findings suggest that reducing unintentional PSIs requires support for both interaction partners rather than reliance on reactive countermeasures alone.

Supporting both interaction partners enables mutually acceptable PSI regulation

Overall, this thesis extends existing research on personal space regulation in social VR by investigating PSI countermeasures from the invader's perspective. By combining controlled quantitative evidence with in-depth qualitative insights, the findings indicate that mutually acceptable personal space regulation depends not only on protecting the invadee but also on supporting the invader through effective communication and increased spatial awareness. The empirical findings and resulting design implications therefore provide a foundation for developing future social VR systems that better balance user safety, agency, and natural social interaction.

6.2 Future Work

The findings of this thesis also raise several questions that remain to be explored. Three directions are identified: extending the present findings to a broader range of scenarios and populations, empirically evaluating the participant-inspired design concepts proposed in this thesis, and exploring how social VR platforms can support personal space regulation at the system level.

Future research should extend the findings beyond the present study

Building on the limitations discussed in Chapter 5.3, future studies should investigate whether the reported findings extend beyond the controlled conditions of the present work. Such research could examine personal space regulation in a broader range of interaction scenarios, such as collaborative activities with multiple users or different virtual environments. It could also investigate different locomotion techniques or different directions of approach during PSIs. Extending the proposed framework across the reality–virtuality continuum, including CAVE-based virtual environments, could further clarify how different immersive technologies influence the effectiveness of PSI countermeasures. Furthermore, involving participants with greater experience in social VR may provide valuable insights into how PSI countermeasures can be designed to better support both invaders and invadees across a wider range of social interactions.

Participant-inspired design concepts require empirical evaluation

Another promising direction is the implementation and evaluation of the participant-inspired design concepts proposed in this thesis. Although the present work identified a range of visual, auditory, haptic, and behavioural support mechanisms, it did not investigate their effectiveness experimentally. Future research could therefore examine how individual communication cues, as well as combinations of complementary cues, influence the perception, acceptance, and effectiveness of PSI countermeasures. Such work could help identify which combinations best support both invaders and invadees while maintaining natural and socially acceptable interactions.

Future work should investigate context-aware platform support

Finally, future work should also examine how social VR platforms can support personal space regulation beyond individual countermeasures. Rather than relying on a single intervention, future systems could adapt personal space regulation to the surrounding context: the relationship between the invader and invadee, the level of crowding, and whether a PSI appears accidental or intentional could all influence how a system responds. Personalised personal space boundaries, adaptive intervention strategies, and perspective-dependent feedback for both interaction partners may contribute to more flexible and socially acceptable approaches to personal space regulation.

Refining interpersonal interaction plays a key role in the maturation of social VR

Beyond these specific avenues for future research, this thesis emphasises the continued need to refine interpersonal interaction in social VR. As discussed in Chapter 2, technological innovations typically mature over an extended period before reaching widespread commercial adoption. In the case of social VR, this refinement extends beyond hardware advances: it also requires safe, comfortable, and socially meaningful interactions. By supporting both invaders and invadees through cordial, yet effective, personal space regulation, future research can contribute not only to PSI countermeasures but also to the maturation of social VR as a socially engaging and sustainable medium.

The future of social VR depends on socially meaningful interactions

The long arc of VR development, traced throughout this thesis from early laboratory systems to contemporary social platforms, reflects a challenge that extends beyond technological performance: how to make shared virtual spaces genuinely liveable. More than sixty years after Ivan Sutherland first envisioned immersive virtual environments, remarkable progress has been made. However, the recent struggles of several prominent social VR platforms[1] suggest that technological maturity alone is insufficient to realise the broader vision of immersive social worlds: the future of social VR depends not just on how convincingly it recreates reality but on how thoughtfully it supports the social interactions that enable people to share virtual spaces with confidence, respect, and trust.

[1] https://www.heise.de/en/background/The-Metaverse-and-its-ghost-towns-Why-social-VR-apps-are-struggling-11311515.html [Accessed: July 2026]

Appendix A

Implementation Resources

This appendix documents the external image sources used throughout the thesis, the sources of the assets incorporated into the virtual environment, and the organisation of the accompanying Git repository[1]. Table A.1 lists all external image sources according to the figures in which they appear. The cited references identify the sources from which the graphics were obtained and do not necessarily correspond to the original works or inventions depicted. Table A.2 documents the external sources of the 3D assets used in the virtual environment, while Table A.3 provides an overview of the top-level directories in the accompanying Git repository to facilitate navigation, future adaptations, and further development of the project.

[1] `https://git.rwth-aachen.de/i10/thesis/thesis-anubhav-punetha-psi-countermeasures-confederate`

Figure	Image	Source
Figure 2.1	Reality-Virtuality Continuum	Milgram and Kishino [1994]
Figure 2.2	Telesphere Mask	Lescop [2017]
	Sensorama Simulator	Xu [2022]
	Sword of Damocles	Sheikh and Crolla [2023]
	DataGlove	Pinto [2010]
	CAVE	Cruz-Neira et al. [1992]
	Virtual Boy	`https://en.wikipedia.org/wiki/Virtual_Boy` [Accessed: April 2026]
	Oculus Acquisition	`https://fortune.com/2017/10/11/facebook-oculus-work-virtual-reality/` [Accessed: April 2026]
	HTC Vive	`https://mixed.de/htc-vive-erscheint-erst-2016/` [Accessed: April 2026]
	Apple Vision Pro	`https://www.apple.com/newsroom/2023/06/introducing-apple-vision-pro/` [Accessed: April 2026]
Figure 2.3	VRChat	`https://store.steampowered.com/app/438100/VRChat/` [Accessed: April 2026]
	Rec Room	`https://recroom.com/` [Accessed: April 2026]
	AltspaceVR	`https://roadtovr.com/oculus-founder-try-save-altspacevr/` [Accessed: April 2026]
	Horizon Worlds	`https://tecnoblog.net/noticias/meta-encerrara-horizon-worlds-em-vr-nos-headsets-quest/` [Accessed: April 2026]
Figure 2.4	Human Avatar for Illustrating Proxemic Zones	Avatar generated using OpenAI ChatGPT (GPT-5.5, June 2026)
Figure 2.5	Personal Boundaries in Meta Horizon Worlds	`https://mashable.com/article/meta-personal-boundary-horizon-worlds-facebook` [Accessed: April 2026]
Figure 2.6	Stop Gesture in Rec Room	`https://www.youtube.com/watch?v=2bWTgmAxBes` [Accessed: April 2026]

Table A.1: External image sources referenced throughout the thesis, organised according to the corresponding figures, with references indicating the sources of the graphics rather than the original works or inventions depicted.

VR Asset	Source
Avatar of Virtual Agent	https://www.fab.com/listings/2e872a96-686e-4955-8256-82fa19904f92
Chair	https://sketchfab.com/3d-models/modern-chair-f91f386f3602463cb161437d3c42d3b7
Clock	https://sketchfab.com/3d-models/cc0-wall-clock-3-8c95c5e879f24f8294d9c8c25804ab95
Coffee Machine	https://sketchfab.com/3d-models/cafetera-profesional-mtrl-e9c06e5c826c41a1a2468556189de241
Computer	https://sketchfab.com/3d-models/macbook-laptop-7ceb46a1425b475fa7f6bf192e01ed74
Door Handle	https://sketchfab.com/3d-models/cc0-door-handle-3-0f4459df86af469dad41c5d025973d87
Dustbin	https://sketchfab.com/3d-models/dust-bin-895fb3596c16407e8a30f0a29bea08a4
First Aid Box	https://sketchfab.com/3d-models/first-aid-box-b16686cb9b284cf892c5a939d357f73c
Office Chair	https://sketchfab.com/3d-models/office-chair-5cd859cd7b9a430db0195af2ba89949b
Painting (1) in the corridor	https://sketchfab.com/3d-models/wall-picture-6ceabfb0ad844c66b70a6ded2bf3d436
Paintings (4) in the corridor	https://sketchfab.com/3d-models/picture-frame-collection-987f8659bdd34549955c38ea1f4a6fe9
Printer	https://sketchfab.com/3d-models/mfp-office-printer-d55f6fca7c3d45c883bbff770672970d
Radiator	https://sketchfab.com/3d-models/radiator-low-poly-509e0519c5694d11bd015fd6c7b60df7
Table	https://www.fab.com/listings/c3e5c435-07fd-435d-be85-a94b4acbf94b
Tubelight	https://sketchfab.com/3d-models/tube-light-c0a1a915abba44319f47c87aa9c1fa52
Vending Machine	https://sketchfab.com/3d-models/soda-vending-machine-f753a659faae499282e882d63972d4c2
Water Cooler	https://sketchfab.com/3d-models/office-electronics-water-cooler-74e2cabe19014c20b10d38a023fd05a5
Whiteboard Wall	https://sketchfab.com/3d-models/whiteboard-low-poly-f69949960b5049f0b7a733e47d9da489
Whiteboard Standing	https://sketchfab.com/3d-models/low-poly-whiteboard-1cbf089ec4b741ad9d092d15db6d55ba

Table A.2: External sources of the 3D assets used throughout the virtual office environment, with references indicating the sources from which the assets were obtained rather than their original creators or designers.

Repository Overview
ma_questionnaireApp
Contains the iPad questionnaire application developed for Study 1. The application generated random four-character participant IDs and exported questionnaire responses in JSON format. It was developed specifically for this thesis and would require additional testing and documentation before reuse.
*ma_study*1
Contains the questionnaire and EDA data collected during Study 1, together with the Python analysis scripts, the MAXQDA project, and documentation of the thematic analysis process. See *ma_study*1*_readme.md* for further details.
*ma_study*1*_psiVisionPro*
Contains the visionOS application used in Study 1, as well as the Arduino and Python scripts provided by Franca Hübner for EDA data collection.
*ma_study*2
Contains the demographics data and transcripts from the semi-structured interviews during Study 2, together with the Python analysis scripts, the MAXQDA project, and documentation of the thematic analysis process. See *ma_study*2*_readme.md* for further details.
*ma_study*2*_psiVisionPro*
Contains the visionOS application used in Study 2 from the invader's perspective.
ma_videos
Contains the view recordings of the different conditions across both studies. See *ma_videos_readme.md* for further details.

Table A.3: Overview of the top-level directories in the Git repository accompanying this thesis, summarising the purpose and primary contents of each directory.

Appendix B

Study 1 Supplementary Material

This appendix documents the materials associated with the study described in Chapter 3.2. It comprises four sections. The first outlines the study protocol, including the preparation, experimental procedure, and post-session activities. Participant appointments were coordinated using the DFN Terminplaner platform[1]. The second presents the English participant information sheet, the third the informed consent form, and the fourth the English questionnaire. The questionnaire was implemented as a custom iPad application that exported responses in JSON format. The data were subsequently processed and analysed using Python, with the corresponding variable names shown in **bold** alongside each questionnaire item.

[1] `https://terminplaner6.dfn.de/de/b/831f8be67b3d5763fec3812d5088171c-1644895`

Study Protocol

Before the Experiment

1. Before each study session, ensure that all equipment (Apple Vision Pro, Meta Quest, Apple TV, Controller, Arduino), materials, and the experimental environment are properly prepared.
2. The seminar room with the Apple Vision Pro and Meta Quest must be booked in advance. The room should be arranged so that the participant has enough space to comfortably perform the VR tasks.
3. Snacks and water should be prepared for participants.
4. All devices must be fully charged before the experiment begins.
5. The Arduino sensor system must be prepared before the session.
6. All required printed materials must be available. Spare copies of the questionnaire should be printed in both supported languages to ensure that participants can complete the study even if technical issues occur.
7. The iPad used for the questionnaire must be prepared in advance. The correct questionnaire should be opened and ready for participants. Screen recording must be started to capture the questionnaire interaction.
8. Finally, the Apple TV should be set up and connected properly to ensure that the display and mirroring functions work as intended during the experiment.
9. Once all equipment and materials are prepared, begin the study session when the participant arrives.

Experiment Procedure

1. **Participant Welcome**
   When the participant arrives, welcome them and

briefly introduce yourself and the study environment. Ensure the participant feels comfortable before starting the experiment.

2. **Language Selection**
   Ask the participant to select their preferred language for the study. All explanations and materials should be provided in the selected language.

3. **Study Information and Consent**
   Provide the participant with the study information sheet and give them time to read it carefully. Explain the purpose of the study, what participation involves, and any potential risks or discomforts such as cybersickness. After explaining the study, present the informed consent form. Allow the participant to ask questions. Once all questions are answered and the participant agrees to participate, ask them to sign the informed consent form.

4. **Study Mascot Selection**
   Ask the participant to pick the study mascot.

5. **Device Setup**
   Prepare the Apple Vision Pro for the participant.

   - Set up hand tracking calibration.
   - Set up eye tracking calibration.
   - Connect the Xbox controller and ensure it works correctly.
   - Teach them how to connect the Apple TV.

   Make sure the participant is comfortable wearing the headset and understands how to interact with the system.

6. **Start Questionnaire Recording**
   Before the participant begins answering questionnaires, start screen recording on the iPad that is used to display the questionnaire.

7. **Demographics Questionnaire**
   Ask the participant to complete the demographics section of the questionnaire on the iPad.

8. **Intro Scene**
   Start the intro scene. This allows the participant to become familiar with the virtual environment and the controls. The participant may repeat the introduction as many times as they want until they feel comfortable with the system.

9. **Short Break**
   After the introduction, give the participant a short break. During this break, ask the participant whether they are experiencing cybersickness or any discomfort. If necessary, allow additional time before continuing.

Baseline Condition

- Begin the baseline condition of the experiment.
- Ensure that the Meta Quest system is running.
- Ensure that the Arduino sensor system is active and recording data.
- Participant completes the baseline scenario in VR.
- After finishing the baseline condition, ask the participant to complete the baseline questionnaire on the iPad.
- After the questionnaire, ask the participant if they are experiencing cybersickness or any discomfort.

Condition 1

- Start Condition 1 of the experiment.
- Ensure that the Meta Quest system is running.
- Ensure that the Arduino sensor system is recording.
- Participant completes the VR task for Condition 1.
- After finishing the task, ask the participant to complete the questionnaire for Condition 1.

- Ask again whether the participant is experiencing cybersickness.

Condition 2

- Start Condition 2 of the experiment.
- Ensure that the Meta Quest system is running.
- Ensure that the Arduino sensor system is recording.
- Participant completes the VR task for Condition 2.
- After finishing the task, ask the participant to complete the questionnaire for Condition 2.
- Ask again whether the participant is experiencing cybersickness.

Condition 3

- Start Condition 3 of the experiment.
- Ensure that the Meta Quest system is running.
- Ensure that the Arduino sensor system is recording.
- Participant completes the VR task for Condition 3.
- After finishing the task, ask the participant to complete the questionnaire for Condition 3.
- Ask again whether the participant is experiencing cybersickness.

Ranking

After all conditions are completed, ask the participant to rank the conditions according to their experience. Finally, ask the participant to finish the remaining questionnaire questions. The experiment session is then completed.

End of the Study

- Check if all data has been collected properly.
- Verify that the questionnaire responses are saved.
- Verify that the screen recording from the iPad is saved.
- Verify that the Arduino sensor data is saved.
- Stop and store all recordings if necessary.
- Clean the VR headset and the controllers.
- Organise the equipment.
- Dispose of any trash.
- Ensure the room is ready for the next session.

Participant Information Form

Figure B.1 presents the English version of the study information form provided to participants prior to signing the informed consent form. Participants were given the option to select either English or German as their preferred language. A corresponding version of the study information was also made available within the questionnaire application on the iPad prior to the commencement of each study.

Informed Consent Form

Figure B.2 presents the English version of the informed consent form provided to participants. Participants received the document in their previously selected language. A corresponding version of the study information was also made available within the questionnaire application on the iPad prior to the commencement of each study, where participants were required to confirm their consent by activating an acceptance toggle before proceeding with the study.

Study Information

How VR Personal Space Invasion Countermeasures Impact the Invader

Principal investigator: Anubhav Punetha
RWTH Aachen University
Lehrstuhl Informatik 10 (chaired by Prof. Borchers)
52056 Aachen, Germany
Email: anubhav.punetha@rwth-aachen.de

Purpose: The goal of this study is to investigate how individuals experience and react to personal space invasion countermeasures in a virtual reality (VR) environment when they take on the role of an invader. The study aims to gain insights into the effects of such countermeasures on the invader and to explore the potential support mechanisms for invaders in VR scenarios.

Procedure: During this study, you will participate in a VR task in which you assume the role of an invader. You will start in a corridor within a virtual environment and will be instructed to reach a specific point in the corridor as quickly as possible. While completing this task, you may encounter another virtual human who is performing their own tasks. During these encounters, the virtual human may apply personal space invasion countermeasures, which may result in you being stopped, pushed back, or required to adjust your movement.
The virtual environment may also include other virtual humans that either remain idle or move randomly but do not directly interact with you. The study can be conducted either in English or in German. After completing the task(s), you may be asked to answer questionnaires and/or participate in a short interview about your experience.

Possible Risks and Discomforts: The use of virtual reality may lead to cyber sickness, which can include symptoms such as dizziness, nausea, headaches, or eye strain. Additionally, the simulation of narrow or enclosed spaces within the virtual environment may cause feelings of discomfort or unease.
If you experience any discomfort, you may pause or terminate your participation at any time without any negative consequences. During the study, help will be provided in case of immediate assistance.

Costs and Compensations: There are no costs associated with participating in this study. Snacks and drinks may be provided during or after the session. No financial compensation will be offered.

Data Protection and Contact: All data collected in this study will be treated confidentially and stored under an anonymous ID. Publications and reports will not contain identifying information. Video and audio recordings, if collected, will be used solely for analysis purposes and deleted after transcription and evaluation. For data-protection questions, participants may contact the Data Protection Officer of RWTH Aachen University:

Stabsstelle Datenschutz der RWTH Aachen University
Templergraben 83, 52062 Aachen, Germany
RWTH Aachen University
Email: dsb@rwth-aachen.de
Tel: +49 241 80 94114

Figure B.1: Participant information form provided to participants in Study 1.

Informed Consent Form

How VR Personal Space Invasion Countermeasures Impact the Invader

Principal investigator: Anubhav Punetha
RWTH Aachen University
Lehrstuhl Informatik 10 (chaired by Prof. Borchers)
52056 Aachen, Germany
Email: anubhav.punetha@rwth-aachen.de

By signing this form, I confirm that:

☐ I have received and read the study information document in the language I selected (English or German) and fully understand its contents.

☐ I understand the purpose and procedure of the study, including that I will be asked to deliberately invade the personal space of others within a virtual reality (VR) environment as part of the experimental task.

☐ I understand that participation may involve typical VR-related discomfort or mild unease related to the task, and that there are no known risks beyond those encountered in standard VR experiences.

☐ I understand that my participation is voluntary, and that I may stop the experiment or withdraw from the study at any time, without giving a reason and without any negative consequences.

☐ I understand that all data collected during the study will be treated confidentially, that I will be identified only by an anonymous ID and that no identifying information will be included in any publications or reports.

☐ I understand that video and/or audio recordings, if collected, will be used solely for analysis purposes (e.g., timing or behavioural analysis) and will be deleted after transcription and evaluation.

☐ I have been informed of the responsible researcher(s) and know whom to contact if I have questions about the study or my rights as a participant.

Participant's Name	Participant's Signature	Date
	Principal Investigator	Date

Figure B.2: Informed consent form used in Study 1.

Questionnaire

The questionnaire was divided into six sections: a demographics section, four condition-specific sections, and a final ranking section. The questions included in the condition-specific sections employed a five-point Likert scale using the scale labels provided by Iowa State University[2], with the response categories *Strongly Agree*, *Agree*, *Undecided*, *Disagree*, and *Strongly Disagree*. For improved readability, these response categories are not repeated within the corresponding questionnaire sections presented in this appendix.

Demographics

- **[demographics_age]** Age:

  _____

- **[demographics_gender]** Gender:

  - Male
  - Female
  - Non-Binary
  - Prefer not to say

- **[demographics_occupation]** Occupation:

  _____

- **[demographics_education]** Highest Education:

  _____

- **[demographics_mascot]** Study Mascot:

  _____

- **[demographics_vr]** Prior VR Experience:

  - Never
  - Once a year
  - Once a month
  - Once a week
  - Daily

[2] `https://www.extension.iastate.edu/documents/anr/likertscaleexamplesforsurveys.pdf` [Accessed: April 2026]

- **[demographics_svr]** Prior Social VR Experience:
  - Never
  - Once a year
  - Once a month
  - Once a week
  - Daily

Condition Baseline

Perception

- **[baseline_per_appropriate]** The avatar's reaction felt appropriate for the situation.
- **[baseline_per_clearReasoning]** I clearly understood why the virtual avatar reacted this way.
- **[baseline_per_easyToUnderstand]** The reaction of the virtual avatar was easy to understand.
- **[baseline_per_fairReaction]** The reaction of the virtual avatar felt fair and natural.

Emotional

- **[baseline_emo_confidence]** I felt confident continuing my movement.
- **[baseline_emo_control]** I felt in control during the experiment.
- **[baseline_emo_safety]** I felt safe during the experiment.
- **[baseline_emo_socialRejection]** I felt socially rejected by the avatar.
- **[baseline_emo_stress]** I felt stressed during the interaction.
- **[baseline_emo_uncomfortable]** The situation made me feel uncomfortable.

Self-Reflection

- **[baseline_srf_responsibilityEscalation]** I felt responsible for the escalation of the interaction.
- **[baseline_srf_responsibilityTrigger]** I felt responsible for triggering the avatar's reaction.
- **[baseline_srf_roleReflection]** I reflected on my role in the interaction.
- **[baseline_srf_spatialAwareness]** I became more aware of my own spatial distances in the virtual world.

Realism

- **[baseline_rea_agentIntentional]** The virtual avatar was appeared to act intentionally.
- **[baseline_rea_discomfort]** I experienced discomfort.
- **[baseline_rea_goalDirected]** The avatar's behaviour felt goal-directed.
- **[baseline_rea_immersed]** I felt immersed in the virtual environment.
- **[baseline_rea_interactionRealistic]** The virtual interaction felt realistic.
- **[baseline_rea_motionSickness]** I experienced motion sickness.

Further Comments

Condition Push

Perception

- **[push_per_appropriate]** The avatar's reaction felt appropriate for the situation.
- **[push_per_clearReasoning]** I clearly understood why the virtual avatar reacted this way.
- **[push_per_easyToUnderstand]** The reaction of the virtual avatar was easy to understand.
- **[push_per_fairReaction]** The reaction of the virtual avatar felt fair and natural.

Emotional

- **[push_emo_confidence]** I felt confident continuing my movement.
- **[push_emo_control]** I felt in control during the experiment.
- **[push_emo_safety]** I felt safe during the experiment.
- **[push_emo_socialRejection]** I felt socially rejected by the avatar.
- **[push_emo_stress]** I felt stressed during the interaction.
- **[push_emo_uncomfortable]** The situation made me feel uncomfortable.

Countermeasure Analysis

- **[push_cou_harsh]** The countermeasure felt harsh.
- **[push_cou_intuitive]** The countermeasure felt intuitive.
- **[push_cou_justified]** The countermeasure felt justified in this situation.

- **[push_cou_predictable]** The countermeasure was predictable.
- **[push_cou_realistic]** The countermeasure felt realistic.
- **[push_cou_sociallyAcceptable]** The countermeasure felt socially acceptable to use.
- **[push_cou_wouldReuse]** I would have used the same countermeasure if I could.

Self-Reflection

- **[push_srf_responsibilityEscalation]** I felt responsible for the escalation of the interaction.
- **[push_srf_responsibilityTrigger]** I felt responsible for triggering the avatar's reaction.
- **[push_srf_roleReflection]** I reflected on my role in the interaction.
- **[push_srf_spatialAwareness]** I became more aware of my own spatial distances in the virtual world.

Realism

- **[push_rea_agentIntentional]** The virtual avatar was appeared to act intentionally.
- **[push_rea_discomfort]** I experienced discomfort.
- **[push_rea_goalDirected]** The avatar's behaviour felt goal-directed.
- **[push_rea_immersed]** I felt immersed in the virtual environment.
- **[push_rea_interactionRealistic]** The virtual interaction felt realistic.
- **[push_rea_motionSickness]** I experienced motion sickness.

Further Comments

Condition Evade

Perception

- **[evade_per_appropriate]** The avatar's reaction felt appropriate for the situation.
- **[evade_per_clearReasoning]** I clearly understood why the virtual avatar reacted this way.
- **[evade_per_easyToUnderstand]** The reaction of the virtual avatar was easy to understand.
- **[evade_per_fairReaction]** The reaction of the virtual avatar felt fair and natural.

Emotional

- **[evade_emo_confidence]** I felt confident continuing my movement.
- **[evade_emo_control]** I felt in control during the experiment.
- **[evade_emo_safety]** I felt safe during the experiment.
- **[evade_emo_socialRejection]** I felt socially rejected by the avatar.
- **[evade_emo_stress]** I felt stressed during the interaction.

- **[evade_emo_uncomfortable]** The situation made me feel uncomfortable.

Countermeasure Analysis

- **[evade_cou_harsh]** The countermeasure felt harsh.
- **[evade_cou_intuitive]** The countermeasure felt intuitive.
- **[evade_cou_justified]** The countermeasure felt justified in this situation.
- **[evade_cou_predictable]** The countermeasure was predictable.
- **[evade_cou_realistic]** The countermeasure felt realistic.
- **[evade_cou_sociallyAcceptable]** The countermeasure felt socially acceptable to use.
- **[evade_cou_wouldReuse]** I would have used the same countermeasure if I could.

Self-Reflection

- **[evade_srf_responsibilityEscalation]** I felt responsible for the escalation of the interaction.
- **[evade_srf_responsibilityTrigger]** I felt responsible for triggering the avatar's reaction.
- **[evade_srf_roleReflection]** I reflected on my role in the interaction.
- **[evade_srf_spatialAwareness]** I became more aware of my own spatial distances in the virtual world.

Realism

- **[evade_rea_agentIntentional]** The virtual avatar was appeared to act intentionally.

- **[evade_rea_discomfort]** I experienced discomfort.
- **[evade_rea_goalDirected]** The avatar's behaviour felt goal-directed.
- **[evade_rea_immersed]** I felt immersed in the virtual environment.
- **[evade_rea_interactionRealistic]** The virtual interaction felt realistic.
- **[evade_rea_motionSickness]** I experienced motion sickness.

Further Comments

Condition Bubble

Perception

- **[bubble_per_appropriate]** The avatar's reaction felt appropriate for the situation.
- **[bubble_per_clearReasoning]** I clearly understood why the virtual avatar reacted this way.
- **[bubble_per_easyToUnderstand]** The reaction of the virtual avatar was easy to understand.
- **[bubble_per_fairReaction]** The reaction of the virtual avatar felt fair and natural.

Emotional

- **[bubble_emo_confidence]** I felt confident continuing my movement.
- **[bubble_emo_control]** I felt in control during the experiment.
- **[bubble_emo_safety]** I felt safe during the experiment.
- **[bubble_emo_socialRejection]** I felt socially rejected by the avatar.
- **[bubble_emo_stress]** I felt stressed during the interaction.
- **[bubble_emo_uncomfortable]** The situation made me feel uncomfortable.

Countermeasure Analysis

- **[bubble_cou_harsh]** The countermeasure felt harsh.
- **[bubble_cou_intuitive]** The countermeasure felt intuitive.
- **[bubble_cou_justified]** The countermeasure felt justified in this situation.
- **[bubble_cou_predictable]** The countermeasure was predictable.
- **[bubble_cou_realistic]** The countermeasure felt realistic.
- **[bubble_cou_sociallyAcceptable]** The countermeasure felt socially acceptable to use.
- **[bubble_cou_wouldReuse]** I would have used the same countermeasure if I could.

Self-Reflection

- **[bubble_srf_responsibilityEscalation]** I felt responsible for the escalation of the interaction.
- **[bubble_srf_responsibilityTrigger]** I felt responsible for triggering the avatar's reaction.
- **[bubble_srf_roleReflection]** I reflected on my role in the interaction.
- **[bubble_srf_spatialAwareness]** I became more aware of my own spatial distances in the virtual world.

Realism

- **[bubble_rea_agentIntentional]** The virtual avatar was appeared to act intentionally.
- **[bubble_rea_discomfort]** I experienced discomfort.
- **[bubble_rea_goalDirected]** The avatar's behaviour felt goal-directed.
- **[bubble_rea_immersed]** I felt immersed in the virtual environment.
- **[bubble_rea_interactionRealistic]** The virtual interaction felt realistic.
- **[bubble_rea_motionSickness]** I experienced motion sickness.

Further Comments

Countermeasure Ranking

Please rank the countermeasures (Push, Evade, Bubble) according to the following criteria:

	Rank 1	Rank 2	Rank 3
Intuitiveness			
Realism			
Perceived Safety			
Socially Acceptable			
Least Physical Demand			
Least Stress Caused			
Sense of Control			

Table B.3: Participants ranked the three countermeasures for each attribute using an Olympic medal-style ranking system, assigning each rank only once per attribute. Figure B.4 shows the corresponding interface.

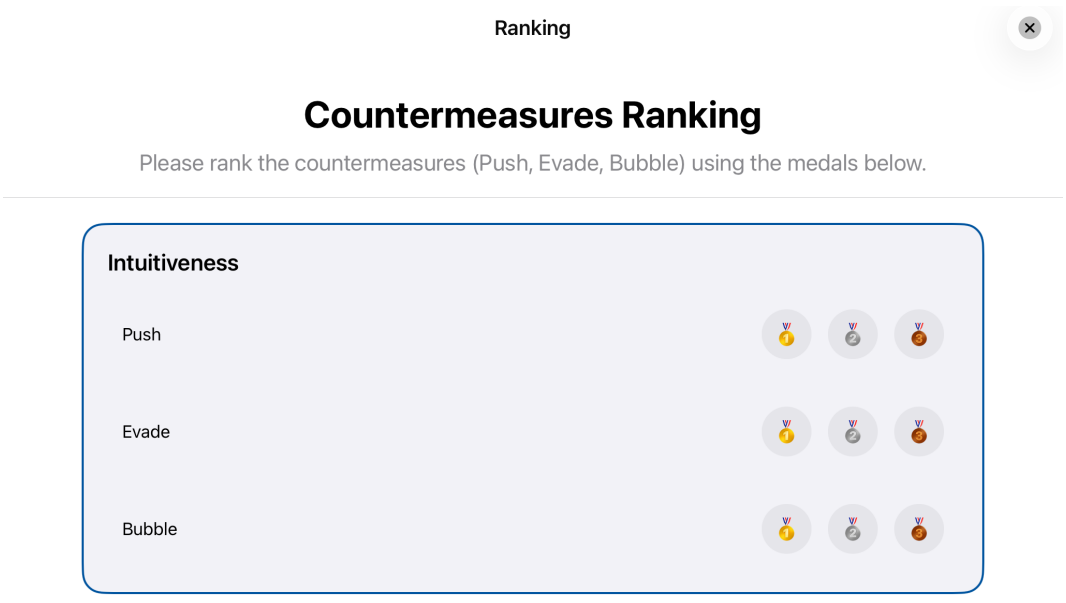


Figure B.4: Screenshot of the Study 1 countermeasure ranking interface, showing the first attribute presented for ranking.

Do you have any further comments?

Appendix C

Study 2 Supplementary Material

This appendix comprises four sections documenting the materials and procedures associated with the study described in Chapter 3.3. The first outlines the study protocol, including the preparation, experimental procedure, and post-session activities. Participant appointments were coordinated using the DFN Terminplaner platform[1]. The second presents the participant information sheet, the third the informed consent form, and the fourth the questionnaire used during the study.

[1] https://terminplaner6.dfn.de/de/b/b56ac7cfa1d118e7a2a2e5b75610703f-1751793

Study Protocol

Before the Experiment

1. Before each study session, ensure that all equipment (Apple Vision Pro, MetaQuest, Apple TV, Controller), materials, and the experimental environment are fully prepared and functioning correctly.
2. The user study room with the Apple Vision Pro and MetaQuest must be booked in advance. The room should be arranged so that the participant has enough space to comfortably perform the VR tasks.
3. Snacks and water should be prepared for participants.
4. All devices must be fully charged before the experiment begins.
5. All required printed materials must be available.
6. The Apple TV should be set up and connected properly to ensure that the display and mirroring functions work as intended during the experiment.
7. Once all equipment and materials are prepared, begin the study session when the participant arrives.

Experiment Procedure

1. **Participant Welcome**
   When the participant arrives, welcome them and briefly introduce yourself and the study environment. Ensure the participant feels comfortable before starting the experiment.
2. **Study Information and Consent**
   Provide the participant with the study information sheet and allow sufficient time for them to read it carefully. Explain the purpose of the study, the nature of participation, and any potential risks or discomforts, including the possibility of cybersickness.

Following this explanation, present the informed consent form. Allow the participant to ask any questions they may have. Once all questions have been answered satisfactorily and the participant agrees to take part, ask them to sign the informed consent form.

3. **Study Mascot Selection**
   Ask the participant to pick the study mascot.

4. **Device Setup**
   Prepare the Apple Vision Pro for the participant.

   - Set up eye tracking calibration.
   - Set up hand tracking calibration.
   - Connect the PS4 controller and ensure it works correctly.
   - Teach them how to connect the Apple TV.

   Ensure that the participant is comfortable wearing the headset and understands how to interact with the system and controls.

5. **Demographics Questionnaire**
   Ask the participant to complete the demographics section of the questionnaire on the iPad.

6. **Intro Scene**
   Start the intro scene. This allows the participant to become familiar with the virtual environment and the controls. Participants may repeat the introduction as many times as necessary until they feel comfortable using the system.

7. **Short Break**
   Following the introduction, offer the participant a short break if required. During this break, ask the participant whether they are experiencing cybersickness or any discomfort. If necessary, allow additional time before continuing.

Baseline Condition

- Begin the baseline condition of the experiment.

- Start with the participant in the role of the defender. In this phase, the participant will use the Apple Vision Pro headset, while you operate the MetaQuest headset and controller.
- Subsequently, begin the invader perspective condition, during which the participant will use the PS4 controller.
- After completing the baseline condition, provide the participant with a sheet of paper for note-taking. Allow the participant five minutes to record their observations and reflections.

Condition 1

- Begin Condition 1 of the experiment.
- Start with the participant in the role of the defender. In this phase, the participant will use the Apple Vision Pro headset, while you operate the MetaQuest headset and controller.
- Subsequently, begin the invader perspective condition, during which the participant will use the PS4 controller.
- Upon completion of the condition, provide the participant with a sheet of paper for note-taking. Allow the participant five minutes to record their observations and reflections. During this time, review the participant's notes from the previous condition.

Condition 2

- Begin Condition 2 of the experiment.
- Start with the participant in the role of the defender. In this phase, the participant will use the Apple Vision Pro headset, while you operate the MetaQuest headset and controller.

- Subsequently, begin the invader perspective condition, during which the participant will use the PS4 controller.
- Upon completion of the condition, provide the participant with a sheet of paper for note-taking. Allow the participant five minutes to record their observations and reflections. During this time, review the participant's notes from the previous condition.

Condition 3

- Begin Condition 3 of the experiment.
- Start with the participant in the role of the defender. In this phase, the participant will use the Apple Vision Pro headset, while you operate the MetaQuest headset and controller.
- Subsequently, begin the invader perspective condition, during which the participant will use the PS4 controller.
- Upon completion of the condition, provide the participant with a sheet of paper for note-taking. Allow the participant five minutes to record their observations and reflections. During this time, review the participant's notes from the previous condition.

8. **Short Break**
   Following the completion of all conditions, provide the participant with a short break before beginning the interview session. During this break, review the participant's notes from the last conditions.
9. **Semi-structured Interview**
   Begin recording the interview. Ask the participant about their experiences and emotional responses throughout the experiment. Guide the interview as minimally as possible, allowing the participant to speak freely and openly. Seek to gather detailed insights regarding their overall experience, perceived limitations, emotional reactions, support

mechanisms, and possible interventions from the perspective of the invader.

10. **Drawing Task**
Provide the participant with a screenshot of the invader's perspective. Ask the participant to draw potential support mechanisms or interaction concepts that they believe could improve the experience.

End of the Study

- Check if all data has been collected properly.
- Verify that the questionnaire responses are saved.
- Stop and store all recordings if necessary.
- Clean the VR headset and the controllers. Put the devices to charge if needed.
- Organise and store all equipment appropriately.
- Dispose of any rubbish or unused materials.
- Ensure that the room is clean, organised, and prepared for the next session.

Participant Information Form

Figure C.1 presents the study information form provided to participants prior to signing the informed consent form.

Informed Consent Form

Figure C.2 presents the informed consent form provided to participants.

Study Information

How VR Personal Space Invasion Countermeasures Impact the Invader

Principal investigator: Anubhav Punetha
RWTH Aachen University
Email: anubhav.punetha@rwth-aachen.de

Purpose: The purpose of this study is to explore how individuals perceive and respond to personal space invasion and related countermeasures within a virtual reality (VR) environment. The study examines these experiences from both perspectives: the individual whose personal space is being invaded (invadee) and the individual approaching or entering another's personal space (invader). The study aims to gain insights into the effects of such countermeasures and to explore the potential support mechanisms for invaders in VR scenarios.

Procedure: In this study, you will participate in a VR-based task in which you will take on two roles: invadee and invader. The study is organized into a series of rounds, each including both roles followed by a short written reflection. You will complete a total of four rounds. In each round, you will first perform the task from the perspective of the invadee, followed by the invader role. After completing both roles, you will be given five minutes to write notes about your experience. These notes can later be used to support your responses during the interview session.

The study will be conducted in English. After completing all rounds, you will participate in a brief interview to further reflect on your experiences.

Possible Risks and Discomforts: Participation in virtual reality may cause symptoms commonly associated with cybersickness, such as dizziness, nausea, headaches, or eye strain. Additionally, simulated environments involving narrow or enclosed spaces may cause discomfort or unease for some individuals. If you experience any discomfort at any point, you are free to pause or stop your participation without any negative consequences. Assistance will be available throughout the session if needed.

Costs and Compensations: There are no costs associated with participating in this study. Snacks and drinks may be provided during or after the session. No financial compensation will be offered.

Data Protection and Contact: All data collected during this study will be handled confidentially and stored under anonymized identifiers. Any publications or reports resulting from this research will not contain personally identifiable information. Audio and video recordings will be used solely for research and analysis purposes and will be securely deleted after transcription and evaluation.

Figure C.1: Participant information form provided to participants in Study 2.

Informed Consent Form

How VR Personal Space Invasion Countermeasures Impact the Invader

Principal investigator: Anubhav Punetha
RWTH Aachen University
Email: anubhav.punetha@rwth-aachen.de

By signing this form, I confirm that:

☐ I have received and read the study information document and fully understand its contents.

☐ I understand the purpose and procedure of the study, including that I will participate in virtual reality (VR) scenarios in which I may be asked to deliberately enter the personal space of a virtual avatar, as well as scenarios in which a virtual avatar will enter my personal space as part of the experimental task.

☐ I understand that participation may involve typical VR-related discomfort or mild unease related to the task, and that there are no known risks beyond those encountered in standard VR experiences.

☐ I understand that my participation is voluntary, and that I may stop the experiment or withdraw from the study at any time, without giving a reason and without any negative consequences.

☐ I understand that all data collected during the study will be treated confidentially, that I will be identified only by an anonymous ID and that no identifying information will be included in any publications or reports.

☐ I understand that video and/or audio recordings, if collected, will be used solely for analysis purposes (e.g., timing or behavioural analysis) and will be deleted after transcription and evaluation.

☐ I have been informed of the responsible researcher(s) and know whom to contact if I have questions about the study or my rights as a participant.

Participant's Name	Participant's Signature	Date
	Principal Investigator	Date

Figure C.2: Informed consent form used in Study 2.

Demographics Questionnaire

The questionnaire was designed to gather information about the demographics of the participants.

Demographics

- Age:

  _____

- Gender:

  - Male
  - Female
  - Non-Binary
  - Prefer not to say

- Occupation:

  _____

- Highest Education:

  _____

- Study Mascot:

  _____

- Prior VR Experience:

  - Never
  - Once a year
  - Once a month
  - Once a week
  - Daily

- Prior Social VR Experience:

  - Never
  - Once a year
  - Once a month
  - Once a week
  - Daily

Appendix D

Supporting Analysis Results

This appendix provides supplementary material supporting the findings presented in Chapter 4 and the discussion developed in Chapter 5. It includes detailed statistical analysis results from Study 1, together with the complete thematic analysis codebooks developed for Studies 1 and 2. These materials are provided to improve the readability of the main chapters while ensuring transparency and reproducibility of the analyses.

The complete datasets collected during the studies are available in the accompanying Git repository. This includes the JSON data files from Study 1 and the interview transcripts from Study 2. In addition, the repository contains the Python scripts used to perform the statistical analyses, the MAXQDA project files used for the qualitative analysis, and an exported version of the thematic codebooks in Microsoft Excel format.

		χ^2	p-value
PERCEPTION	Appropriate	8.7350	0.0330
	Clear Reasoning	10.3070	0.0161
	Easy to Understand	9.0550	0.0286
	Fair Reaction	2.0530	0.5616
EMOTIONAL	Confidence	3.8550	0.2776
	Control	10.6330	0.0139
	Safety	30.1220	0.0000
	Social Rejection	19.3810	0.0002
	Stress	32.4870	0.0000
	Uncomfortable	14.7400	0.0021
SELF-REFLECTION	Responsibility Escalation	12.3450	0.0063
	Responsibility Trigger	24.9570	0.0000
	Role Reflection	4.3270	0.2282
	Spatial Awareness	8.8720	0.0310
REALISM	Agent Intentional	8.5740	0.0355
	Discomfort	8.7320	0.0331
	Goal Directed	3.6580	0.3009
	Immersed	1.5260	0.6763
	Interaction Realistic	2.5560	0.4653
	Motion Sickness	11.3930	0.0098
COUNTERMEASURE ANALYSIS	Harsh	13.8180	0.0010
	Intuitive	2.6560	0.2650
	Justified	8.2190	0.0164
	Predictable	3.1140	0.2107
	Realistic	2.2690	0.3216
	Socially Acceptable	16.1470	0.0003
	Would Reuse	10.0000	0.0067

Table D.1: Summary of the Friedman test results for all questionnaire items across the experimental conditions in Study 1. Statistically significant results ($p < 0.05$) are highlighted in orange. For further details, see Chapter 4.1.1.

	Condition A	Condition B	Median A	Median B	p-value
Appropriate	BASELINE	SAFETY BUBBLE	3.5	4.0	1.0000
	BASELINE	EVADE	3.5	4.0	1.0000
	BASELINE	PUSH	3.5	2.0	0.8200
	SAFETY BUBBLE	EVADE	4.0	4.0	1.0000
	SAFETY BUBBLE	PUSH	4.0	2.0	0.2422
	EVADE	PUSH	4.0	2.0	0.0095
Clear Reasoning	BASELINE	SAFETY BUBBLE	4.0	4.0	1.0000
	BASELINE	EVADE	4.0	4.0	0.2612
	BASELINE	PUSH	4.0	4.0	1.0000
	SAFETY BUBBLE	EVADE	4.0	4.0	0.1002
	SAFETY BUBBLE	PUSH	4.0	4.0	1.0000
	EVADE	PUSH	4.0	4.0	0.0993
Easy to Understand	BASELINE	SAFETY BUBBLE	4.0	4.0	1.0000
	BASELINE	EVADE	4.0	4.0	0.1058
	BASELINE	PUSH	4.0	4.0	1.0000
	SAFETY BUBBLE	EVADE	4.0	4.0	0.0628
	SAFETY BUBBLE	PUSH	4.0	4.0	1.0000
	EVADE	PUSH	4.0	4.0	0.0712

Table D.2: Summary of the post-hoc pairwise comparisons for the Perception section across the experimental conditions in Study 1. Statistically significant differences ($p < 0.05$) are highlighted in orange. For further details, see Chapter 4.1.1.

	Condition A	Condition B	Median A	Median B	p-value
Control	Baseline	Safety Bubble	4.0	4.0	0.4138
	Baseline	Evade	4.0	4.0	1.0000
	Baseline	Push	4.0	3.5	0.0918
	Safety Bubble	Evade	4.0	4.0	0.2857
	Safety Bubble	Push	4.0	3.5	1.0000
	Evade	Push	4.0	3.5	0.1400
Safety	Baseline	Safety Bubble	2.0	4.0	0.0009
	Baseline	Evade	2.0	4.0	0.001
	Baseline	Push	2.0	4.0	0.0199
	Safety Bubble	Evade	4.0	4.0	1.0000
	Safety Bubble	Push	4.0	4.0	0.2767
	Evade	Push	4.0	4.0	0.1153
Social Rejection	Baseline	Safety Bubble	4.0	4.0	1.0000
	Baseline	Evade	4.0	3.0	1.0000
	Baseline	Push	4.0	5.0	0.0700
	Safety Bubble	Evade	4.0	3.0	1.0000
	Safety Bubble	Push	4.0	5.0	0.0220
	Evade	Push	3.0	5.0	0.0035

Continued on next page

	Condition A	Condition B	Median A	Median B	p-value
Stress	BASELINE	SAFETY BUBBLE	4.0	2.0	0.0028
	BASELINE	EVADE	4.0	2.0	0.0007
	BASELINE	PUSH	4.0	2.5	0.0058
	SAFETY BUBBLE	EVADE	2.0	2.0	1.0000
	SAFETY BUBBLE	PUSH	2.0	2.5	1.0000
	EVADE	PUSH	2.0	2.5	0.3982
Uncomfortable	BASELINE	SAFETY BUBBLE	4.0	4.0	0.3568
	BASELINE	EVADE	4.0	2.5	0.0148
	BASELINE	PUSH	4.0	4.0	1.0000
	SAFETY BUBBLE	EVADE	4.0	2.5	0.8652
	SAFETY BUBBLE	PUSH	4.0	4.0	0.7323
	EVADE	PUSH	2.5	4.0	0.0483

Table D.3: Summary of the post-hoc pairwise comparisons for the `Emotional` section across the experimental conditions in Study 1. Statistically significant differences ($p < 0.05$) are highlighted in orange. For further details, see Chapter 4.1.1.

	Condition A	Condition B	Median A	Median B	p-value
Responsibility Escalation	BASELINE	SAFETY BUBBLE	2.0	3.0	0.1137
	BASELINE	EVADE	2.0	4.0	0.0206
	BASELINE	PUSH	2.0	4.0	0.0507
	SAFETY BUBBLE	EVADE	3.0	4.0	0.9305
	SAFETY BUBBLE	PUSH	3.0	4.0	1.0000
	EVADE	PUSH	4.0	4.0	1.0000
Responsibility Trigger	BASELINE	SAFETY BUBBLE	2.0	4.0	0.0009
	BASELINE	EVADE	2.0	4.0	0.0010
	BASELINE	PUSH	2.0	4.0	0.0199
	SAFETY BUBBLE	EVADE	4.0	4.0	1.0000
	SAFETY BUBBLE	PUSH	4.0	4.0	0.2767
	EVADE	PUSH	4.0	4.0	0.1153
Spatial Awareness	BASELINE	SAFETY BUBBLE	4.0	4.0	1.0000
	BASELINE	EVADE	4.0	4.0	0.0486
	BASELINE	PUSH	4.0	4.0	0.5968
	SAFETY BUBBLE	EVADE	4.0	4.0	0.4537
	SAFETY BUBBLE	PUSH	4.0	4.0	1.0000
	EVADE	PUSH	4.0	4.0	1.0000

Table D.4: Summary of the post-hoc pairwise comparisons for the Self-Reflection section across the experimental conditions in Study 1. Statistically significant differences ($p < 0.05$) are highlighted in orange. For further details, see Chapter 4.1.1.

	Condition A	Condition B	Median A	Median B	p-value
Agent Intentional	Baseline	Safety Bubble	4.0	4.0	1.0000
	Baseline	Evade	4.0	4.0	1.0000
	Baseline	Push	4.0	4.0	0.0511
	Safety Bubble	Evade	4.0	4.0	1.0000
	Safety Bubble	Push	4.0	4.0	0.0855
	Evade	Push	4.0	4.0	0.8235
Discomfort	Baseline	Safety Bubble	3.0	2.0	0.2972
	Baseline	Evade	3.0	2.0	0.2428
	Baseline	Push	3.0	3.5	1.0000
	Safety Bubble	Evade	2.0	2.0	1.0000
	Safety Bubble	Push	2.0	3.5	0.6610
	Evade	Push	2.0	3.5	0.4808
Motion Sickness	Baseline	Safety Bubble	2.0	1.5	0.0416
	Baseline	Evade	2.0	1.5	0.1179
	Baseline	Push	2.0	1.5	0.4825
	Safety Bubble	Evade	1.5	1.5	0.6285
	Safety Bubble	Push	1.5	1.5	1.0000
	Evade	Push	1.5	1.5	1.0000

Table D.5: Summary of the post-hoc pairwise comparisons for the `Realism` section across the experimental conditions in Study 1. Statistically significant differences ($p < 0.05$) are highlighted in orange. For further details, see Chapter 4.1.1.

	Condition A	Condition B	Median A	Median B	p-value
Harsh	SAFETY BUBBLE	EVADE	3.0	2.0	0.4860
	SAFETY BUBBLE	PUSH	3.0	4.5	0.0106
	EVADE	PUSH	2.0	4.5	0.0025
Justified	SAFETY BUBBLE	EVADE	4.0	4.0	1.0000
	SAFETY BUBBLE	PUSH	4.0	2.0	0.0076
	EVADE	PUSH	4.0	2.0	0.0096
Socially Acceptable	SAFETY BUBBLE	EVADE	4.0	4.0	1.0000
	SAFETY BUBBLE	PUSH	4.0	2.0	0.0123
	EVADE	PUSH	4.0	2.0	0.0033
Would Reuse	SAFETY BUBBLE	EVADE	3.0	4.0	1.0000
	SAFETY BUBBLE	PUSH	3.0	2.0	0.0347
	EVADE	PUSH	4.0	2.0	0.0129

Table D.6: Summary of the post-hoc pairwise comparisons for the `Countermeasure Analysis` section across the experimental conditions in Study 1. Statistically significant differences ($p < 0.05$) are highlighted in orange. For further details, see Chapter 4.1.1.

	χ^2	p-value
Intuitiveness	1.583	0.4531
Least Physical Demand	33.250	0.0000
Least Stress Caused	18.083	0.0001
Perceived Safety	15.750	0.0004
Realism	3.583	0.1667
Sense of Control	11.083	0.0039
Social Acceptability	18.583	0.0001

Table D.7: Summary of the Friedman test results for the ranking task in Study 1. Statistically significant results ($p < 0.05$) are highlighted in orange. For further details, see Chapter 4.1.2.

	Condition A	Condition B	Median A	Median B	p-value
Least Physical Demand	SAFETY BUBBLE	EVADE	1.0	2.0	1.0000
	SAFETY BUBBLE	PUSH	1.0	3.0	0.0000
	EVADE	PUSH	2.0	3.0	0.0000
Least Stress Caused	SAFETY BUBBLE	EVADE	1.0	2.0	1.0000
	SAFETY BUBBLE	PUSH	1.0	3.0	0.0022
	EVADE	PUSH	2.0	3.0	0.0004
Perceived Safety	SAFETY BUBBLE	EVADE	1.0	2.0	0.4545
	SAFETY BUBBLE	PUSH	1.0	3.0	0.0011
	EVADE	PUSH	2.0	3.0	0.0583
Sense of Control	SAFETY BUBBLE	EVADE	2.0	1.0	1.0000
	SAFETY BUBBLE	PUSH	2.0	3.0	0.0345
	EVADE	PUSH	1.0	3.0	0.0315
Social Accept-ability	SAFETY BUBBLE	EVADE	2.0	1.5	1.0000
	SAFETY BUBBLE	PUSH	2.0	3.0	0.0117
	EVADE	PUSH	1.5	3.0	0.0008

Table D.8: Summary of the post-hoc pairwise comparisons for the countermeasure ranking task in Study 1. Statistically significant differences ($p < 0.05$) are highlighted in orange. For further details, see Chapter 4.1.2.

Code	Participant ID(s)
Attitudes Towards Personal Space in VR	
Baseline condition lacked interaction	875X
Baseline interaction perceived as impolite	PG1L
Evade perceived as an introverted response	U1BK
Expectation that users would pass through one another in virtual reality	7MH9
Personal space perceived as unnecessary in virtual reality	U09G
Personal space perceived as unusual in virtual reality	U09G
Preference for more assertive countermeasures	U1BK
Recognition of the need for personal space countermeasures	U1BK
Interpretation of Countermeasure Feedback	
Annoying auditory feedback	124B, PG1L
Auditory feedback influenced emotional responses	124B
Auditory feedback signalled a personal space violation	L1K4
Confusing behaviour of the invadee	D5JG, OAEM, PG1L
Difficulty distinguishing between Bubble and Evade	L1K4
Early bubble activation	VF7M
Evade perceived as confusing	OAEM
Misaligned personal space notification	OAEM
Mistimed auditory feedback	124B, D5JG
Need for improved auditory feedback	515Q
Perceived similarity between Bubble and Evade	OAEM
Preference for displaying both safety bubbles	MAD2
Preference for gradually increasing bubble visibility	MAD2, OAEM
Restoration of movement perceived as unintuitive	OAEM
Sudden auditory feedback	124B, 7MH9, KXR8, OAEM
Sudden bubble activation	K0DF, DTNA, OAEM

Continued on next page

Code	Participant ID(s)
Emotional and Behavioural Impact of Countermeasures	
Avatar's emotional expression influenced participants' emotions	124B
Baseline condition elicited discomfort	124B
Bubble reduced participants' sense of control	K0DF
Countermeasures perceived as less intuitive from the invader's perspective	K0DF
Push perceived as aggressive	124B, 4DSF, OAEM, PG1L, VF7M
Push perceived as enjoyable	DTNA
Push perceived as harsh	515Q
Push perceived as justified	L1K4
Reduced perceived social rejection	GL3Z
Restricted movement perceived as frustrating	D5JG
Restricted movement perceived as harsh	VF7M
Restricted movement perceived as uncomfortable	K0DF
Sudden push activation	K0DF
Perceived Realism and Naturalness	
Bubble perceived as artificial	7MH9
Bubble perceived as unnatural	VF7M
Countermeasure perceived as unnatural	K0DF
Evade perceived as more natural	7MH9
Evade perceived as realistic	4DSF, 875X
Lack of avatar emotional expression	K0DF
Lack of environmental audio	KXR8
Motion sickness	515Q, U1BK
Perceived realism of the virtual environment	L1K4
Poor avatar animation	GL3Z, OAEM
Push perceived as realistic	GL3Z, U1BK
Supporting avatars enhanced environmental realism	124B
Unexpected movement speed changes reduced realism	OAEM
Weak interaction with the avatar	875X

Table D.9: Codebook developed from the qualitative analysis of the open-ended comments collected in Study 1. Codes are organised according to the final themes identified during the analysis, with the corresponding participant ID(s) indicating which participants expressed each code. For further details, see Chapter 4.1.3.

		Evade	Push	Safety Bubble
Mean Tonic EDA Analysis				
Descriptive Statistics	Mean	0.132	0.431	0.189
	Median	0.219	0.574	0.082
	SD	0.876	0.828	0.755
Shapiro-Wilk Test	*W*	0.9351	0.9737	0.9761
	p	0.1270	0.7590	0.8139
Friedman Test	χ^2	0.5833		
	p	0.7470		
Peak Tonic EDA Analysis				
Descriptive Statistics	Mean	0.777	0.959	0.604
	Median	0.453	0.884	0.376
	SD	0.908	0.954	0.722
Shapiro-Wilk Test	*W*	0.8263	0.8913	0.8412
	p	0.0008	0.0142	0.0015
Friedman Test	χ^2	3.5833		
	p	0.1667		

Table D.10: Summary of the descriptive statistics and statistical analyses for the tonic EDA measurements in Study 1. Mean and peak tonic EDA values are reported for each countermeasure condition. For further details, see Chapter 4.1.4.

Code	Participant ID(s)
Negotiating Personal Space Through Social Communication	
Communicating the Countermeasure	
Negative perception of pop-up notifications	C461
Countermeasure reactions were anticipated	Z2T1
Existing mental models should be incorporated	1LBN
Visual indicators can be easily overlooked	J91B
Countermeasure reactions perceived as sudden	P081, I0X1
Countermeasure perceived as confusing	I0X1
Negotiating Personal Space	
Avatar colour proposed as a visual warning	AI12
Avatar expressions proposed to communicate discomfort	AI12, EBKH
Lack of social cues	I0X1
Mutual cooperation during passing	1LBN, 52K1, 7M8W, EBKH, I0X1, P081
Request for non-verbal communication cues	1LBN, AI12, EBKH, P081
Request for verbal communication cues	P081, Z2T1
Suggestion to incorporate emoji-based feedback	1LBN
Fairness and User Agency	
Balancing invadee protection with invader awareness	J91B, Z2T1
Bubble perceived as avoiding blame towards the invader	Z2T1
Explicit notifications perceived as socially unnatural	C461
Importance of user autonomy	1LBN, AI12, C461, I0X1, J91B, M0D1, Q0P1
Pop-up notifications perceived to increase confrontation	C461
Preference for passive countermeasures	AI12
Punishment considered inappropriate for accidental behaviour	52K1, C461, P081
Support for the use of PSI countermeasure	52K1, AI12, Z2T1
System perceived as assuming hostile intent	C461
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Code	Participant ID(s)
Designing Effective Personal Space Countermeasure	
Boundary and Warning Design	
Bubble considered sufficient without additional visual feedback	1LBN
Bubble perceived as providing insufficient visual feedback	1LBN, 52K1, C461, J91B, M0D1, Q0P1, Z2T1
Bubble preferred as warning rather than a countermeasure	P081
Preference for colour-coded proximity feedback	7M8W, AI12, C461, J91B
Preference for gradually increasing bubble visibility	1LBN, AI12, EBKH, I0X1, J91B, M0D1, P081, Z2T1
Preference for larger personal space boundaries	EBKH, J91B, Z2T1
Preference for prevention over reaction	52K1, C461, I0X1, P081, Z2T1
Preference for preventive feedback	AI12, C461
Preference for progressive warning cues	52K1, 7M8W, AI12, C461, EBKH, I0X1, P081, Q0P1
Request for a visible boundary	1LBN, C461, EBKH, J91B, Q0P1
Visual proximity feedback suggested	AI12
Sensory Feedback	
Audio cues may distract the participant	Q0P1
Auditory feedback considered acceptable when accompanied by the invadee's physical response	Z2T1
Auditory feedback perceived as difficult to ignore	A112, J91B
Current auditory cue perceived as inappropriate	1LBN, AI12, EBKH, I0X1, M0D1
Haptic feedback perceived to reduce cognitive load	J91B
Haptic feedback perceived as an intrusion on the user	P081
Haptic feedback perceived as distracting	Q0P1
Positive attitude towards auditory feedback	AI12, I0X1, J91B, M0D1
Preference for controller-based rather than headset-based haptic feedback	1LBN, AI12, Z2T1

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Code	Participant ID(s)
Preference for less intrusive auditory feedback	I0X1, M0D1, Q0P1
Preference for subtle haptic notifications	J91B
Preference for unobtrusive visual feedback	1LBN, C461, I0X1
Request for haptic feedback	AI12, C461, I0X1, Z2T1
Request for multimodal warning cues	P081
Reservations regarding auditory feedback	52K1, 7M8W
Reservations regarding haptic feedback	1LBN, 52K1, EBKH
Sound reinforced the perceived effectiveness of the countermeasure	1LBN , 7M8W
Unexpected sound startled participant	7M8W, EBKH, P081, Z2T1
Adaptive and Personalised Systems	
Context-aware visualisation proposed	C461
Desire for customisable personal space settings	1LBN, 52K1, C461
Individualised view for each user	I0X1
Learning-based adaption suggested	1LBN
Suggestion to incorporate physiological sensing	1LBN
Alternative Countermeasure Concept	
Avatar-shaped bubble proposed as a countermeasure	Z2T1
Existing social media moderation as inspiration	I0X1, M0D1
Invader made invisible to the invadee	I0X1
Mutual visibility considered necessary within the bubble	C461
Preference for bubble-inspired solutions	Z2T1
System-assisted movement correction	C461
Experiences and Evaluation of Countermeasures	
Perceived Realism	
Bubble compared to a sci-fi shield	1LBN
Evade considered an expected response	Q0P1
Evade perceived as most realistic countermeasure	C461
Push considered an expected response	Q0P1
Push interpreted as a slap and perceived as excessive	J91B
Push interpreted as a slap and perceived as humorous	J91B
Push interpreted differently from a slapping action	J91B
Push perceived as lacking realism	J91B
Push preferred over a slapping motion	EBKH, J91B, M0D1
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Code	Participant ID(s)
Perceived Effectiveness	
All countermeasure perceived as overly aggressive	C461
Evade considered not to require warning cues for the invader	C461
Freeze considered appropriate following a serious boundary violation	C461
Freeze the invader only if the invadee continues to evade	C461
Invader should be frozen immediately after being pushed	C461
Push considered necessary as an assertive countermeasure	AI12, C461, EBKH, I0X1, M0D1, P081
Bubble insufficiently alleviated the feeling of personal space invasion	7M8W
Countermeasure perceived as having limited impact on the invader	7M8W
Push provides the invadee with a sense of control	AI12
Evade alone perceived as insufficient to deter the invader	7M8W, I0X1
Evade perceived as requiring minimal effort	AI12, Q0P1
Push perceived as having the greatest impact on the invader	7M8W
Push perceived as unsuitable for practical implementation	1LBN
Recognition of the need for more assertive countermeasures	52K1
Emotional and Behavioural Responses	
Baseline condition caused discomfort for the invader	AI12
Invader experienced discomfort when entering another person's personal space	52K1, EBKH
Movement-based defence altered the interaction experience	7M8W
Psychological burden associated with the invader role	P081
Push perceived as unpleasant for the invader	AI12, 1LBN, 52K1
System induces feelings of guilt	1LBN

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Code	Participant ID(s)
Countermeasure Preference	
Bubble perceived as a balanced solution	AI12
Bubble preferred for accidental personal space invasion	Z2T1
Bubble preferred from the invader perspective	52K1, AI12, I0X1
Bubble preferred to avoid rather than confront the invader	AI12, 7M8W
Evade considered suitable for accidental personal space invasion	C461
Overall preference for Evade	1LBN, AI12, Q0P1
Overall preference for the Bubble	52K1, 7M8W, AI12, C461, I0X1, M0D1, P081, Z2T1
Recognition that each countermeasure serves a distinct purpose	C461, EBKH, M0D1
Satisfaction with current Push implementation	C461
Contextual Factors Influencing Personal Space in Social VR	
Audio and haptic cues perceived as distracting in crowded environments	I0X1
Audio cue preferred in a less crowded environment	I0X1
Blind spots increase the likelihood of PSI	J91B
Boundaries considered unnecessary for Evade and Push	Q0P1
Boundaries preferred only for nearby users	J91B
Bubble perceived as suitable for crowded environments	1LBN
Different behavioural expectations within VR	52K1
Difficulty judging interpersonal distance in VR	1LBN, 7M8W, I0X1
Gender influences proxemic behaviour in VR	Q0P1
Limitations of artificial locomotion	1LBN, 7M8W, P081
Personal space invasion perceived as unavoidable in confined spaces	C461
Preference for a personal bubble for every user	J91B
Real-world avoidance behaviour transferred to VR	52K1, C461
Social hierarchy influences countermeasure in social VR	I0X1

Table D.11: Codebook developed from the thematic analysis of the semi-structured interviews conducted in Study 2. Codes are organised according to the final themes identified during the analysis, with the corresponding participant ID(s) indicating which participants expressed each code. For further details, see Chapter 4.2.

Bibliography

[1] John R. Aiello and Donna E. Thompson. *Personal Space, Crowding, and Spatial Behavior in a Cultural Context*, pages 107–178. Springer US, Boston, MA, 1980. ISBN 978-1-4899-0451-5. doi.org/10.1007/978-1-4899-0451-5_5.

[2] Ebrahim Babaei, Benjamin Tag, Tilman Dingler, and Eduardo Velloso. A Critique of Electrodermal Activity Practices at CHI. CHI '21, New York, NY, USA, 2021. Association for Computing Machinery. doi.org/10.1145/3411764.3445370.

[3] Jeremy N Bailenson, Jim Blascovich, Andrew C Beall, and Jack M Loomis. Interpersonal distance in immersive virtual environments. *Personality and social psychology bulletin*, 29(7):819–833, 2003.

[4] Mark Baldassare and Susan Feller. Cultural Variations in Personal Space. *Ethos*, 3:481 – 503, 10 2009. doi.org/10.1525/eth.1975.3.4.02a00020.

[5] Frank Biocca. Will Simulation Sickness Slow Down the Diffusion of Virtual Environment Technology? *Presence: Teleoperators and Virtual Environments*, 1 (3):334–343, 08 1992. doi.org/10.1162/pres.1992.1.3.334.

[6] Lindsay Blackwell, Nicole Ellison, Natasha Elliott-Deflo, and Raz Schwartz. Harassment in Social Virtual Reality: Challenges for Platform Governance. *Proc. ACM Hum.-Comput. Interact.*, 3(CSCW), November 2019. doi.org/10.1145/3359202.

[7] Dasha Blehm. Countermeasures against Personal Space Invasion in Spatial Computing. Master's thesis, RWTH Aachen University, Aachen, September 2025.

[8] Andrea Bönsch, Sina Radke, Heiko Overath, Laura M. Asché, Jonathan Wendt, Tom Vierjahn, Ute Habel, and Torsten W. Kuhlen. Social VR: How Personal Space is Affected by Virtual Agents' Emotions. In *Proceedings of the IEEE Conference on Virtual Reality and 3D User Interfaces (VR) 2018*, 2018.

[9] Virginia Braun, Victoria Clarke, Nikki Hayfield, and Gareth Terry. *Thematic Analysis*, pages 843–860. Springer Singapore, Singapore, 2019. ISBN 978-981-10-5251-4. doi.org/10.1007/978-981-10-5251-4_103.

[10] Steve Bryson. Virtual reality: A definition history-a personal essay. *arXiv preprint arXiv:1312.4322*, 2013.

[11] Lauren E Buck, Sohee Park, and Bobby Bodenheimer. Determining peripersonal space boundaries and their plasticity in relation to object and agent characteristics in an immersive virtual environment. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 332–342. IEEE, 2020.

[12] Bill Buxton. The long nose of innovation. *Insight*, 11:27, 2008.

[13] Michela Candini, Simone Battaglia, Mariagrazia Benassi, Giuseppe di Pellegrino, and Francesca Frassinetti. The physiological correlates of interpersonal space. *Scientific Reports*, 11(1):2611, 2021.

[14] Victoria Chang, Caro Williams-Pierce, Huaishu Peng, and Ge Gao. Ethical Considerations for Observational Research in Social VR. In *Companion Publication of the 2025 Conference on Computer-Supported Cooperative Work and Social Computing*, CSCW Companion '25, page 405–409, New York, NY, USA, 2025. Association for Computing Machinery. doi.org/10.1145/3715070.3749261.

[15] Hyun Cho and Bernhard E. Riecke. Space Echo 2.0: Exploring Social Interaction Through Communication Barriers in VR. In *Proceedings of the Special Interest Group on Computer Graphics and Interactive Techniques Conference Spatial Storytelling*, SIGGRAPH Spatial Storytelling '25, New York, NY, USA, 2025. Association for Computing Machinery. doi.org/10.1145/3721244.3742452.

[16] Rose Connolly, Lauren Buck, Victor Zordan, and Rachel McDonnell. The Impact of Navigation on Proxemics in an Immersive Virtual Environment with Conversational Agents. *IEEE Transactions on Visualization and Computer Graphics*, 31(5):2787–2797, May 2025. doi.org/10.1109/TVCG.2025.3550231.

[17] Carolina Cruz-Neira, Daniel J. Sandin, Thomas A. DeFanti, Robert V. Kenyon, and John C. Hart. The CAVE: audio visual experience automatic virtual environment. *Commun. ACM*, 35(6):64–72, June 1992. doi.org/10.1145/129888.129892.

[18] Larry M. Dean, Frank N. Willis, and James M. La Rocco. Invasion of Personal Space as a Function of Age, Sex, and Race. *Psychological Reports*, 38(3):959–965, 1976. doi.org/10.2466/pr0.1976.38.3.959.

[19] Elena Dzardanova and Vlasios Kasapakis. Virtual reality: a journey from vision to commodity. *IEEE Annals of the History of Computing*, 45(1):18–30, 2022.

[20] Elena Dzardanova, Vlasios Kasapakis, and Damianos Gavalas. Social virtual reality. In *Encyclopedia of computer graphics and games*, pages 1688–1691. Springer, 2024.

[21] Jannat Falah, Soheeb Khan, Tasneem Alfalah, Salsabeel F. M. Alfalah, Warren Chan, David K. Harrison, and Vassilis Charissis. Virtual Reality medical training system for anatomy education. In *2014 Science and Information Conference*, pages 752–758, 2014. doi.org/10.1109/SAI.2014.6918271.

[22] Ben Falchuk, Shoshana Loeb, and Ralph Neff. The Social Metaverse: Battle for Privacy. *IEEE Technology and Society Magazine*, 37(2):52–61, 2018. doi.org/10.1109/MTS.2018.2826060.

[23] Nancy Jo Felipe and Robert Sommer. Invasions of Personal Space. *Social Problems*, 14:206–214, 1966.

[24] Jeffrey Fisher and Donn Byrne. Too close for comfort: Sex differences in response to invasions of personal space. *Journal of Personality and Social Psychology*, 32:15–21, 07 1975. doi.org/10.1037/h0076837.

[25] Scott S. Fisher. Real-time interactive graphics: taking location-based entertainment to the next level. *SIGGRAPH Comput. Graph.*, 33(1):18–20, February 1999. doi.org/10.1145/563666.563672.

[26] S.S. Fisher, E.M. Wenzel, C. Coler, and M.W. McGreevy. Virtual Interface Environment Workstations. *Proceedings of the Human Factors Society Annual Meeting*, 32(2):91–95, 1988. doi.org/10.1177/154193128803200219.

[27] Guo Freeman and Dane Acena. Hugging from A Distance: Building Interpersonal Relationships in Social Virtual Reality. In *Proceedings of the 2021 ACM International Conference on Interactive Media Experiences*, IMX '21, page 84–95, New York, NY, USA, 2021. Association for Computing Machinery. doi.org/10.1145/3452918.3458805.

[28] Guo Freeman and Divine Maloney. Body, Avatar, and Me: The Presentation and Perception of Self in Social Virtual Reality. *Proc. ACM Hum.-Comput. Interact.*, 4(CSCW3), January 2021. doi.org/10.1145/3432938.

[29] Guo Freeman, Samaneh Zamanifard, Divine Maloney, and Dane Acena. Disturbing the Peace: Experiencing and Mitigating Emerging Harassment in Social Virtual Reality. *Proc. ACM Hum.-Comput. Interact.*, 6(CSCW1), April 2022. doi.org/10.1145/3512932.

[30] Anna M Fry and Frank N Willis. Invasion of personal space as a function of the age of the invader. *The Psychological Record*, 21(3):385–389, 1971.

[31] Thomas A. Furness. The Super Cockpit and its Human Factors Challenges. *Proceedings of the Human Factors Society Annual Meeting*, 30(1):48–52, 1986. doi.org/10.1177/154193128603000112.

[32] Maarten Gerritse, Iris Folpmers, Caesar Alpha Irawan, Guo Freeman, Jan Gugenheimer, and Julian Frommel. Classifying Harms in Social VR: A Systematic Literature Review and Taxonomy. *Proc. ACM Hum.-Comput. Interact.*, 10 (1), March 2026. doi.org/10.1145/3799441.

[33] Saul Greenberg, Kasper Hornbæk, Aaron John Quigley, Harald Reiterer, and Roman Radle. Proxemics in human-computer interaction (Dagstuhl Seminar 13452). *Dagstuhl Reports*, 2014.

[34] Simon N. B. Gunkel, Rick Hindriks, Karim M. El Assal, Hans M. Stokking, Sylvie Dijkstra-Soudarissanane, Frank ter Haar, and Omar Niamut. VRComm: an end-to-end web system for real-time photorealistic social VR communication. In *Proceedings of the 12th ACM Multimedia Systems Conference*, MMSys '21, page 65–79, New York, NY, USA, 2021. Association for Computing Machinery. doi.org/10.1145/3458305.3459595.

[35] Edward T Hall. A system for the notation of proxemic behavior. *American anthropologist*, 65(5):1003–1026, 1963.

[36] Edward T Hall. *The hidden dimension*, volume 609. Anchor, 1966.

[37] Eugy Han and Jeremy Bailenson. *Social Interaction in VR*. 05 2024. ISBN 9780190228613. doi.org/10.1093/acrefore/9780190228613.013.1489.

[38] Béatrice S. Hasler and Doron A. Friedman. Sociocultural Conventions in Avatar-Mediated Nonverbal Communication: A Cross-Cultural Analysis of Virtual Proxemics. *Journal of Intercultural Communication Research*, 41(3):238–259, 2012. doi.org/10.1080/17475759.2012.728764.

[39] Tina Iachini, Yann Coello, Francesca Frassinetti, Vincenzo Paolo Senese, Francesco Galante, and Gennaro Ruggiero. Peripersonal and interpersonal space in virtual and real environments: Effects of gender and age. *Journal of Environmental Psychology*, 45:154–164, 2016.

[40] A.L. Janin, D.W. Mizell, and T.P. Caudell. Calibration of head-mounted displays for augmented reality applications. In *Proceedings of IEEE Virtual Reality Annual International Symposium*, pages 246–255, 1993. doi.org/10.1109/VRAIS.1993.380772.

[41] Kim R. Kanaga and Mark Flynn. The Relationship Between Invasion of Personal Space and Stress. *Human Relations*, 34(3):239–248, 1981. doi.org/10.1177/001872678103400305.

[42] Griffin Kao, Jessica Hong, Michael Perusse, and Weizhen Sheng. *The Rise and Fall of Virtual Reality*, pages 133–139. Apress, Berkeley, CA, 2020. ISBN 978-1-4842-5629-9. doi.org/10.1007/978-1-4842-5629-9_19.

[43] Konstantina Kilteni, Raphaela Groten, and Mel Slater. The Sense of Embodiment in Virtual Reality. *Presence Teleoperators amp Virtual Environments*, 21, 11 2012. doi.org/10.1162/PRES_a_00124.

[44] Ikhwan Kim and Junghan Sung. New proxemics in new space: proxemics in VR. *Virtual Reality*, 28(2):85, 2024.

[45] Mitsuhiko Kimoto, Yohei Otsuka, Michita Imai, and Masahiro Shiomi. Effects of appearance and gender on pre-touch proxemics in virtual reality. *Frontiers in Psychology*, Volume 14 - 2023, 2023. doi.org/10.3389/fpsyg.2023.1195059.

[46] Zheyuan Kuang, Tinghui Li, Weiwei Jiang, Sven Mayer, Flora D. Salim, Benjamin Tag, Anusha Withana, and Zhanna Sarsenbayeva. Understanding the Effects of Interaction on Emotional Experiences in VR. In *Proceedings of the 2026 CHI Conference on Human Factors in Computing Systems*, CHI '26, New York, NY, USA, 2026. Association for Computing Machinery. doi.org/10.1145/3772318.3790313.

[47] Jaron Lanier. Virtual reality: the promise of the future. *Interact. Learn. Int.*, 8 (4):275–279, October 1992.

[48] Karina LaRubbio, Ethan Wilson, Sanjeev Koppal, Sophie Jörg, and Eakta Jain. Give me some room please! Personal space bubbles for safety and performance. In *2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 897–898, 2023. doi.org/10.1109/VRW58643.2023.00291.

[49] Ajey Lele. Virtual reality and its military utility. *Journal of Ambient Intelligence and Humanized Computing*, 4(1):17–26, 2013.

[50] Laurent Lescop. 360° vision, from panoramas to VR. 09 2017.

[51] Mark A Livingston, Lawrence J Rosenblum, Simon J Julier, Dennis Brown, Yohan Baillot, II Swan, Joseph L Gabbard, Deborah Hix, and others. An augmented reality system for military operations in urban terrain. 2002.

[52] Joan Llobera, Bernhard Spanlang, Giulio Ruffini, and Mel Slater. Proxemics with multiple dynamic characters in an immersive virtual environment. *ACM Trans. Appl. Percept.*, 8(1), November 2010. doi.org/10.1145/1857893.1857896.

[53] Divine Maloney and Guo Freeman. Falling Asleep Together: What Makes Activities in Social Virtual Reality Meaningful to Users. In *Proceedings of the*

Annual Symposium on Computer-Human Interaction in Play, CHI PLAY '20, page 510–521, New York, NY, USA, 2020. Association for Computing Machinery. doi.org/10.1145/3410404.3414266.

[54] Divine Maloney, Guo Freeman, and Andrew Robb. Social Virtual Reality: Ethical Considerations and Future Directions for An Emerging Research Space. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 271–277, 2021. doi.org/10.1109/VRW52623.2021.00056.

[55] Michael McCauley and Thomas Sharkey. Cybersickness: Perception of Self-Motion in Virtual Environment. *Presence*, 1:311–318, 01 1992. doi.org/10.1162/pres.1992.1.3.311.

[56] Rory McCloy and Robert Stone. Virtual reality in surgery. *BMJ*, 323(7318): 912–915, 2001. doi.org/10.1136/bmj.323.7318.912.

[57] Joshua McVeigh-Schultz, Anya Kolesnichenko, and Katherine Isbister. Shaping Pro-Social Interaction in VR: An Emerging Design Framework. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, page 1–12, New York, NY, USA, 2019. Association for Computing Machinery. doi.org/10.1145/3290605.3300794.

[58] Paul Milgram and Fumio Kishino. A Taxonomy of Mixed Reality Visual Displays. *IEICE TRANSACTIONS on Information*, E77-D(12):1321–1329, December 1994.

[59] Ilaria Mirlisenna, Greta Bonino, Alessandro Mazza, Francesca Capiotto, Giulia Romano Cappi, Monia Cariola, Alessandro Valvo, Lucia De Francesco, and Olga Monte. How interpersonal distance varies throughout the lifespan. *Scientific Reports*, 14, 10 2024. doi.org/10.1038/s41598-024-74532-z.

[60] Mario Montagud, Jie Li, Gianluca Cernigliaro, Abdallah El Ali, Sergi Fernández, and Pablo Cesar. Towards socialVR: evaluating a novel technology for watching videos together. *Virtual Reality*, 26(4):1593–1613, 2022.

[61] Nasser Nassiri, Norman Powell, and David Moore. Avatar gender and personal space invasion anxiety level in desktop collaborative virtual environments. *Virtual Real.*, 8(2):107–117, June 2004.

[62] Nasser Nassiri, Norman Powell, and David Moore. Enhancing human-computer-interaction in collaborative virtual environment. In *2009 International Conference on the Current Trends in Information Technology (CTIT)*, pages 1–6, 2009. doi.org/10.1109/CTIT.2009.5423147.

[63] Nasser Nassiri, Norman Powell, and David Moore. Human interactions and personal space in collaborative virtual environments. *Virtual reality*, 14(4):229–240, 2010.

[64] Michael G. Nelson, Fu-Chia Yang, Alexandros Koilias, Christos-Nikolaos Anagnostopoulos, and Christos Mousas. Avoiding Virtual Characters: The Effects of Proximity and Gesture. In *2024 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pages 41–50, 2024. doi.org/10.1109/ISMAR62088.2024.00018.

[65] Omar Niamut. Social XR: Barrier-Breaking Technology For Smart Societies. *Online*, 2021.

[66] Ken Perlin. Future Reality: How emerging technologies will change language itself. *IEEE computer graphics and applications*, 36(3):84–89, 2016.

[67] Roosa Piitulainen, Perttu Hämäläinen, and Elisa D Mekler. Vibing Together: Dance Experiences in Social Virtual Reality. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, CHI '22, New York, NY, USA, 2022. Association for Computing Machinery. doi.org/10.1145/3491102.3501828.

[68] Fernando Pinto. *Multimodal Access to Social Media Services*. PhD thesis, 06 2010.

[69] Daniel Pohl and Markus Achtelik. Personalized Personal Spaces for Virtual Reality. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 1128–1129, 2019. doi.org/10.1109/VR.2019.8797773.

[70] Giuseppe Riva. Virtual environments in clinical psychology. *Psychotherapy: Theory, Research, Practice, Training*, 40(1-2):68, 2003.

[71] MJ Roy. A virtual reality exposure therapy application for Iraq War military personnel with post traumatic stress disorder: From training to toy to treatment. *Novel approaches to the diagnosis and treatment of posttraumatic stress disorder*, 6:235, 2006.

[72] Somer Schaffer, Lorne Campbell, and Taylor Kohut. Virtual vistas: Exploring the demographics of the virtual reality user base. *Social Sciences Humanities Open*, 13:102347, 2026. doi.org/10.1016/j.ssaho.2025.102347.

[73] Wenli Shang and Kazlova Alena. Advancements in Virtual Reality Technology: A Systematic Review of User Experience and Application Trends. *Artificial Intelligence and Applications*, 3(4):341–358, Oct. 2025. doi.org/10.47852/bonviewAIA52024327.

[74] Abdullah Sheikh and Kristof Crolla. Architectural Education with Virtual Reality. pages 159–168, 01 2023. doi.org/10.52842/conf.ecaade.2023.1.159.

[75] Paul Skolnick, Lana Frasier, and Ilan A Hadar. Do you speak to strangers? A study of invasions of personal space. *European Journal of Social Psychology*, 7 (3):375–381, 1977. doi.org/10.1002/ejsp.2420070309.

[76] Mel Slater. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364:3549–3557, 12 2009. doi.org/10.1098/rstb.2009.0138.

[77] Mel Slater, Domna Banakou, Alejandro Beacco, Jaime Gallego, Francisco Macia-Varela, and Ramon Oliva. A Separate Reality: An Update on Place Illusion and Plausibility in Virtual Reality. *Frontiers in Virtual Reality*, Volume 3 - 2022, 2022. doi.org/10.3389/frvir.2022.914392.

[78] Jessi Stark, Roberta R.C. Mota, and Ehud Sharlin. Personal Space Intrusion in Human-Robot Collaboration. In *Companion of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*, HRI '18, page 245–246, New York, NY, USA, 2018. Association for Computing Machinery. doi.org/10.1145/3173386.3176998.

[79] Jiayi Sun, Wenli Jiang, Lutong Li, and Chong Cao. Personal Space Evaluation and Protection in Social VR. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 484–485, 2021. doi.org/10.1109/VRW52623.2021.00124.

[80] Eric Sundstrom and Mary Graehl Sundstrom. Personal space invasions: What happens when the invader asks permission? *Environmental psychology and nonverbal behavior*, 2(2):76–82, 1977.

[81] Ivan E Sutherland. A head-mounted three dimensional display. In *Proceedings of the December 9-11, 1968, fall joint computer conference, part I*, pages 757–764, 1968.

[82] Roger BH Tootell, Sarah L Zapetis, Baktash Babadi, Zahra Nasiriavanaki, Dylan E Hughes, Kim Mueser, Michael Otto, Ed Pace-Schott, and Daphne J Holt. Psychological and physiological evidence for an initial 'Rough Sketch'calculation of personal space. *Scientific Reports*, 11(1):20960, 2021.

[83] Miao Wang, Wen-Tong Shu, Yi-Jun Li, and Wanwan Li. Can I Get There? Negotiated User-to-User Teleportations in Social VR. *IEEE Transactions on Visualization and Computer Graphics*, 31(5):2320–2330, 2025. doi.org/10.1109/TVCG.2025.3549572.

[84] Xiaoying Wei, Xiaofu Jin, and Mingming Fan. Communication in Immersive Social Virtual Reality: A Systematic Review of 10 Years' Studies. In *Proceedings of the Tenth International Symposium of Chinese CHI*, Chinese CHI '22, page 27–37, New York, NY, USA, 2024. Association for Computing Machinery. doi.org/10.1145/3565698.3565767.

[85] Stanley Grauman Weinbaum. "Pygmalion's Spectacles", June 1935.

[86] Jing Xu. Immersive Display Design Based on Deep Learning Intelligent VR Technology. *Wireless Communications and Mobile Computing*, 2022:1–9, 08 2022. doi.org/10.1155/2022/1462169.

[87] Amal Yassien and Slim Abdennadher. From Monocular Smart Glasses to Asymmetric VR to Immersive AV: Tailored Interaction Designs for Social Mixed Reality. In *Adjunct Proceedings of the 27th International Conference on Mobile Human-Computer Interaction*, MobileHCI '25 Adjunct, New York, NY, USA, 2025. Association for Computing Machinery. doi.org/10.1145/3737821.3749449.

[88] Suhwoo Yoon, Dakyeom Ahn, Yunseo Choi, Seoyeon Hong, and Hajin Lim. Bodyfulness VR: Exploring Virtual Reality as a Medium for Somatic Meditative Practices. In *Proceedings of the 2026 CHI Conference on Human Factors in Computing Systems*, CHI '26, New York, NY, USA, 2026. Association for Computing Machinery. doi.org/10.1145/3772318.3791456.

[89] Jose P Zagal and Benj Edwards. *Seeing Red: Nintendo's Virtual Boy*. MIT Press, 2024.

[90] Samaneh Zamanifard and Guo Freeman. "The Togetherness that We Crave": Experiencing Social VR in Long Distance Relationships. In *Companion Publication of the 2019 Conference on Computer Supported Cooperative Work and Social Computing*, CSCW '19 Companion, page 438–442, New York, NY, USA, 2019. Association for Computing Machinery. doi.org/10.1145/3311957.3359453.

[91] Shumin Zhai. *Human performance in six degree of freedom input control.*, volume 1. University of Toronto, 1996.

[92] Kexin Zhang, Elmira Deldari, Yaxing Yao, and Yuhang Zhao. A Diary Study in Social Virtual Reality: Impact of Avatars with Disability Signifiers on the Social Experiences of People with Disabilities. In *Proceedings of the 25th International ACM SIGACCESS Conference on Computers and Accessibility*, ASSETS '23, New York, NY, USA, 2023. Association for Computing Machinery. doi.org/10.1145/3597638.3608388.

[93] Dezijian Zhou, Yuanyuan Deng, Anastasia Globa, Julie Zheng, Renxuan Liu, Xingting Wu, Tianrui Liu, Donald Degraen, and Aaron Quigley. Last Christmas I Gave You My Heart: This Christmas I am Taking It Back with Multimodal XR. In *Proceedings of the Extended Abstracts of the 2026 CHI Conference on Human Factors in Computing Systems*, CHI EA '26, New York, NY, USA, 2026. Association for Computing Machinery. doi.org/10.1145/3772363.3799255.

[94] Wenjin Zhu and Callum Parker. Safe but Silent? The Gendered Impact of Personal Space Bubbles (PSBs) in the Metaverse. OzCHI '25, page 395–403, New York, NY, USA, 2025. Association for Computing Machinery. doi.org/10.1145/3764687.3764715.

[95] Thomas Zimmerman, Jaron Lanier, Chuck Blanchard, Steve Bryson, and Young Harvill. A hand gesture interface device. volume 17, pages 189–192, 05 1986. doi.org/10.1145/30851.275628.

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