SeatmateVR: Proxemic Cues for Close Bystander-Awareness in Virtual Reality

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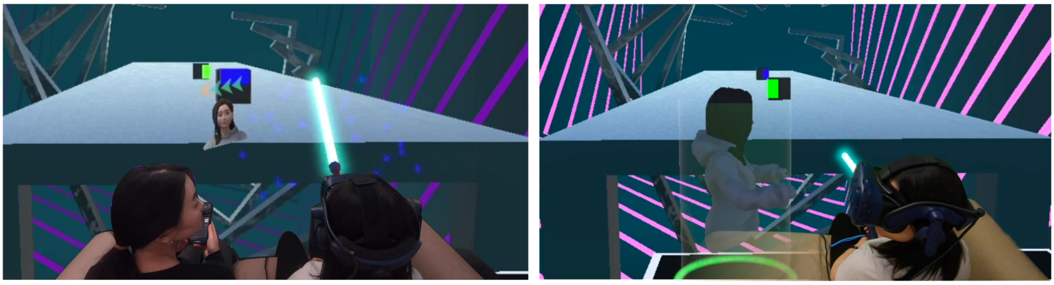

Fig. 1. The *Mixed* visualization prepares the VR users for fast communication with close-space bystanders. Initiated by an *Animoji* (left), the player gets notified when the seatmate starts turning toward them, followed by an *Avatar* (right) that shows the physical location of the seatmate who is looking toward the player.

Prior research explored ways to alert virtual reality users of bystanders entering the play area from afar. However, in confined social settings like sharing a couch with seatmates, bystanders' proxemic cues, such as distance, are limited during interruptions, posing challenges for proxemic-aware systems. To address this, we investigated three visualizations, using a 2D animoji, a fully-rendered avatar, and their combination, to gradually share bystanders' orientation and location during interruptions. In a user study (N=22), participants played virtual reality games while responding to questions from their seatmates. We found that the avatar preserved game experiences yet did not support the fast identification of seatmates as the animoji did. Instead, users preferred the mixed visualization, where they found the seatmate's orientation cues instantly in their view and were gradually guided to the person's actual location. We discuss implications for fine-grained proxemic-aware virtual reality systems to support interaction in constrained social spaces.

CCS Concepts: • **Human-centered computing** → **Virtual reality**.

Additional Key Words and Phrases: bystander awareness, proxemic-aware virtual reality, constrained interaction space

ACM Reference Format:
Jingyi Li, Hyerim Park, Robin Welsch, Sven Mayer, and Andreas Butz. 2023. SeatmateVR: Proxemic Cues for Close Bystander-Awareness in Virtual Reality. In *ISS '23: The ACM Interactive Surfaces and Spaces Conference, November 5-8, 2023, Pittsburgh, USA.* ACM, New York, NY, USA, 20 pages. https://doi.org/10.1145/X

ISS '23, November 5-8, 2023, Pittsburgh, USA

ACM ISBN 978-1-4503-XXXX-X/18/06…$15.00
https://doi.org/10.1145/X

1 INTRODUCTION

Virtual Reality (VR) technology empowers users to immerse themselves in myriad virtual environments while disconnecting them from the situated physical world [41]. As a result, users fear disengaging from their surroundings and losing awareness of other people nearby (bystanders) while using VR on the move [10, 32, 46]. Modern VR headsets enhance bystander awareness by integrating mixed reality features, which overlay real-world elements on virtual environments, such as Oculus Passthrough[1] or Space Sense[2]. Likewise, prior research has incorporated bystanders' real-time proxemic cues into VR [31, 33]. The main focus has been on detecting changes in distance as bystanders move from far to close proximity to the VR user (4 m - 1 m) [23, 37, 43]. However, as mobile VR headsets permeate people's daily lives, existing solutions do not account for bystanders in confined social spaces (< 1 m), such as shared living rooms or public transportation cabins [9, 40, 46]. In these constrained interaction scenarios, bystanders often grab user attention without inducing significant changes in distance relative to the user. They also show less willingness to interrupt the VR user via touch when they do not know each other [34]. Subtle initiation of interruptions from close-space bystanders poses challenges to the effectiveness of established proxemic-aware systems. How can we enhance bystander awareness while preserving virtual experiences by incorporating nuanced proxemic cues within close interaction space?

Prior work recognizes changes in distance as significant social cues as bystanders approach the VR user from afar. When bystanders initiate interruptions, VR systems integrate relevant proxemic cues, including distance, location, orientation, and body movements, to enhance awareness of other people and facilitate social interaction [23, 37, 43]. However, these cues may lose significance in confined social settings, such as the *F-formation* considering the spatial and orientational relationships in small-group interaction [1, 21, 27]. For example, a person sitting next to the user on a couch may turn towards them to gain their attention, even if their distance remains the same in this *side-by-side* setting. As a result, other proxemic cues, especially relative orientation among people, gain importance as social signals [2, 12]. In line with this, research in psychology and neuroscience showed that social interactions in close space (often referred to as personal space or peri-personal space) entail different neuronal and psychological mechanisms than interactions in far space (i.e., extrapersonal space) [6, 25, 36]. However, how and when VR systems should integrate the subtle changes in orientation cues to effectively convey bystanders' actions and intentions remain underexplored.

In this paper, we contribute to the study of bystander awareness by utilizing fine-grained proxemic cues, focusing on confined social settings, i.e., two people sitting side by side. Based on previous research, we propose gradually incorporating bystanders' proxemic cues into VR through various visualization techniques to reflect their significance as social signals during the interruption process. In particular, we evaluated three VISUALIZATION concepts: (1) a 2D *Animoji* displayed in a head-up display, continuously sharing seatmate's orientation to indicate when they want to initiate and end interruptions, (2) a fully-rendered *Avatar* pops up in the periphery of the user's field of view and guides them to the seatmate's off-screen location while continuously providing orientation cues, and (3) a *Mixed* visualization combining both, starting with an animoji within the user's view and then leading to the seatmate's location, continuously sharing orientation cues. In a lab study (N=22), we compared them to a baseline that persistently shared no proxemic cues. We asked participants to play VR games while sharing a couch with another person. During the game, the simulated visualizations tried to grab participants' attention to answer questions from seatmates.

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[1] https://developer.oculus.com/blog/mixed-reality-with-passthrough/, last accessed November 6, 2023

[2] https://vrscout.com/news/oculus-quests-space-sense-feature-detects-people-and-pets/, last accessed November 6, 2023

Our results showed that an *Avatar* was insufficient for prompt identification of the seatmate. While a continuously in-view *Animoji* grabbed user attention, it did not support locating the seatmate in physical space. In contrast, a *Mixed* visualization allowed for pleasant interactions where users efficiently noticed the seatmate’s copresence existence and were directed to the actual location, leading to enhanced communication. Further, we discuss using nuanced proxemic cues for close-space bystander awareness in confined social settings while preserving virtual experiences.

2 RELATED WORK

Next, we review literature grouped into bystander awareness and proxemic interaction in VR research. We highlight two research gaps that guide our work: the lack of continuous bystander visualizations and under-explored close-space interactions in everyday constrained contexts.

2.1 Bystander Awareness in VR Systems

VR headsets empower people to engage in immersive virtual environments anytime and anywhere [14], resulting in the sense of presence, or “the feeling of being there” [41]. In everyday life, people consider using VR glasses on the go acceptable in shared and social spaces, such as on a train or metro [40]. Meanwhile, mobile VR interaction often disconnects users from their physical surroundings, challenging their awareness of other people in proximity [10, 32]. Modern VR systems tackle this issue by visualizing other people during the virtual experience. One such example is Space Sense[3], which detects and visually represents the presence of other individuals in the play area by displaying their silhouettes at their corresponding physical locations in real-time, superimposed on the game scene. However, using a single visualization, constant one-to-one mapping of physical and virtual space, can easily disrupt virtual experiences or fail to be noticeable when real-world changes overlap or are far from the main interaction interface. Prior research investigated different visualization techniques to alert VR users of bystanders invading the play area effectively.

Compared to revealing photo-realistic appearances of bystanders, avatar representations highly integrated into virtual worlds support both fast and accurate awareness [23, 43]. In addition, avatars continuously share bystanders’ real-time location through motion tracking, which is crucial for maintaining users’ comfort in their personal space [33]. However, this single visualization technique is limited in uncontrolled environments, where bystanders approach from behind the headset wearer. To address this issue, Medeiros et al. [31] combined push and pull notification techniques based on the bystander’s proximity to the user, displaying arrow alerts in the view (push) when the person was far away (social space) and guiding users to the avatar that showed their location (pull) when they were close by (personal space). However, this cognitive shift between two visualization techniques disrupted VR game experiences. Using avatar representations that simultaneously visualize bystanders’ locations and full-body movements has also been found to increase cognitive workload and negatively impact VR experiences [37]. So far, VR systems have effectively raised bystander awareness using appropriate visualizations of proxemic cues that consider both the spatial constraints of physical environments and the level of integration into intended virtual environments. However, combining multiple visualization techniques can result in a higher cognitive workload and disrupt immersion and engagement in VR.

2.2 Proxemic Interaction in Virtual Environments

Proxemics describes how humans use space in physical environments [18]. Hall et al. [18] defined proxemics with four main zones of interpersonal distance: intimate distance (touching - 0.46 m),

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[3] https://vrscout.com/news/oculus-quests-space-sense-feature-detects-people-and-pets, last accessed November 6, 2023

personal distance (0.46 m - 1.22 m), social distance (1.22 m - 2.40 m), and public distance (>2.40 m) from observing human-human interactions. Whereas Hall's proxemic theory concerns the major impact of *distance* on interpersonal interactions, F-formations further consider the physical arrangements among people, a *spatial* and *orientational* relationship between individuals, when they engage in focused conversational encounters [21]. In particular, F-formations can distinguish differences in attentional involvement with different orientations, such as standing close and facing each other versus facing in different directions at the same interpersonal distance [42]. For HCI, proxemic interaction describes how mobile systems can utilize the proxemics of people and devices as a means of input for devices in ubiquitous environments [3]. Greenberg et al. [12] put forth five proxemic dimensions for designing ubicomp applications, including *distance*, *orientation*, *movement*, *identity*, and *location*. Among these, distance and relative orientation among multiple users were found to enable co-located collaboration across devices in F-formations [27, 28].

The concept of proxemics has recently gained relevance in developing mobile VR systems for everyday use, from home to transport. Prior research on room-scale VR suggested adjusting the transparency, size, and color saturation of bystander visualizations to effectively alert the user of bystanders' actions and intentions while preserving the VR experience [31, 33]. These adjustments are based on the bystander's proximity to the user's personal space, which loses significance in confined social settings where bystanders are constantly seated close to VR users. In close social encounters, people use orientation as alternative cues to indicate engagement levels, e.g., shifting from a side-by-side to a face-to-face setting often signals the initiation of a conversation [7, 21]. However, determining the appropriate level of interruption in such situations can be challenging in the VR experience, as previously found during in-flight VR entertainment with nearby seatmates in the side-by-side seating arrangement [46]. Subtleties and intricacies of close social interactions pose challenges to the sensitivity and effectiveness of the current proxemic-aware VR systems.

2.3 Summary

In sum, we built our work on human-human proxemics, proxemic interaction, and visualization design strategy for enhancing bystander awareness in VR. Our approach extends the current proxemic-aware VR systems from a distance-centered visualization of bystanders who move across different proxemic zones to an orientation-centered visualization of bystanders who continuously stay within the user's close personal space. Besides constraints from physical environments, we consider the level of integration into virtual environments. In particular, we focus on providing high-granularity visualizations of bystanders, fine-tuning how and when to incorporate relevant proxemic cues as social signals to support bystander awareness in confined social settings without disrupting the VR experience.

3 CONCEPT

Informed by the prior work in F-formations [7, 21, 42] and bystander awareness [23, 43], we proposed to use different visualization techniques for incorporating relevant proxemic dimensions (*orientation* and *location*) into VR, depending on their importance as social signals during the interruption process. We focused on the two-user side-by-side F-formation and utilized the most noticeable orientation cues to signal when a seatmate desired to initiate an interruption [21]. To guide the fine-grained visualization design, we divided the side-by-side range into four zones: (1) no interest (180-90°), e.g., the seatmate focusing on own activities; (2) slight interest (90-60°), wondering what the VR user is doing, (3) potential interest (60-30°), uncertain about interrupting or not, (4) interest (30-0°), ready to interrupt and talk to VR users based on proxemics literature [18, 19]. We also designed the facial expression of the seatmate in all visualizations for realistic

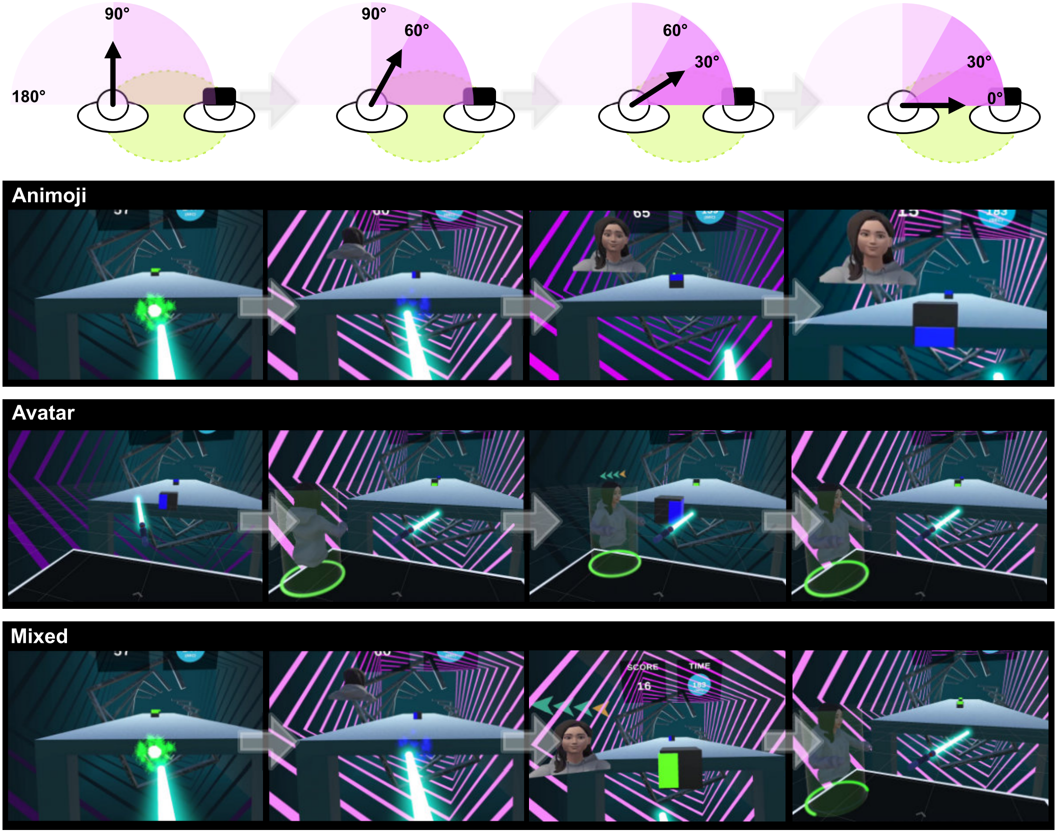

Fig. 2. From left to right, the animation design of proxemic cues follows the four orientation zones in the side-by-side arrangement. From top to bottom, three visualization concepts, *Animoji*, *Avatar*, and *Mixed*, as tested in the experiment.

social interaction. Below, we detail how these three concepts vary along the side-by-side range, following four orientation zones, see Figure 2.

Animoji. This visualization technique is inspired by 2D icon-based symbolic representations that successfully convey changes in the distance and orientation of bystanders when approaching the user from afar [23]. They are separated from bystanders' actual locations and attached to the headset, continuously displayed within the user's field of view, as previously found noticeable during virtual experiences [38]. Adapting this concept to the constrained side-by-side setting, we designed an animated emoji icon (animoji) that follows four zones, showing (1) from a 100% transparent back of animoji to indicate no interest, (2) fading in the solid back of animoji to indicate slight interest, (3) turning to the front face to indicate potential interest to interrupt, and (4) smiling to users to indicate interest to interact. With this push notification [31], we expect to provide effective bystander awareness by sharing only *orientation* cues that are the most relevant social signals in this constrained setting.

Avatar. This visualization is informed by literal representations using fully-rendered avatars placed at the actual location of bystanders, revealing real-time changes in distance, orientation, and location [23]. Likewise, we adapted this visualization to the confined setting and designed an animated 3D avatar. The animation again follows the four zones, showing the avatar on the side (1) from transparent, (2) fading in while looking forward, (3) starting to turn toward the user, and (4) smiling. During the pilot testing, we discovered that the avatar mapped to the seatmate's actual location was displayed outside the user's field of view in the side-by-side setting. To address this issue, prior work proposed a combination of push (Arrow3D) and pull (Ghost) notifications [31], which shows the direction to the person's actual location by displaying an arrow prompt directly to the user's field of view. In contrast, we displayed a similar arrow prompt only in the periphery of the user (in the third zone) as found to avoid occlusion and maintain VR experiences [13]. In addition, we displayed the avatar and the arrow simultaneously to share bystanders' orientation cues already in the push notification as the most eye-catching social signal when triggering interruptions. Taken together, our avatar visualization used a similar combination of push and pull notifications for balancing bystander awareness and engagement in virtual experiences; however, with less intrusive display (periphery view instead of central view) while more proxemic-aware cues (providing orientation cues) in the push notification design. With the adapted combination of push and pull notifications, we anticipate minimizing disruptions in VR experiences as long as possible while providing enough information about bystanders' actions and intentions by sharing *orientation* and *location* cues shortly before upcoming social encounters.

Mixed. This visualization combines the *Animoji* and *Avatar* in animation sequences. The animation proceeds (1) from transparent, (2) fading in the solid back of *Animoji*, (3) turning to the front face with an arrow prompt above the *Animoji* to show the direction of the seatmate's actual location, and (4) transitioning into a smiling *Avatar* situated on the side. This mixed visualization can be seen as a combination of push (Presence++) and pull (Avatar) notifications previously suggested to balance bystander awareness and engagement in virtual experiences [23]. In particular, we aim to achieve a smooth and continuous transition between pull and push notifications, in contrast to the conventional combination of in-view arrow prompts and avatars [31] or the constant picture-in-picture preview of off-screen targets [24], to reduce cognitive load during the switch. By combining two visualization techniques, we anticipate incrementally increasing bystander awareness, first by providing *orientation* cues through an animoji icon in the view and then pulling the user's attention to the seatmate's actual *location* using a situated avatar as interest increases.

4 EVALUATION

We compared our concepts to a non-proxemic-aware baseline to answer our research question:

> "*How can we support close bystander-awareness of VR users in everyday constrained interaction spaces while preserving their engagement in virtual game experiences?*"

We designed a within-subject experiment in which participants played a seated VR game. As the independent variable, we varied the VISUALIZATION factor of the sequence of proxemic cues with four levels: (a) *Baseline*: with no proxemic indications of the seatmate throughout the VR experience, (b) *Animoji*: with visualization sequence attached to the headset, visible in a head-up display within the field of view, (c) *Avatar*: the sequence pops up situated at the edge of the field of view and directs users to the actual location of the seatmate, and (d) *Mixed*: the sequence appears in the head-up display and guides users to the actual location aside.

4.1 Task

Following Kudo et al. [23], we used an identification task embedded in VR experiences. In our scenario, we asked the participant to pause the game with a button press on the controller when they noticed that the seatmate wanted to talk to them and resume the game using the same button when they thought the interaction was over. We tried to simulate real small talk and thus asked participants to verbally answer a question from the seatmate played by the experimenter in VR without taking off the headset. For this, we designed four short pre-recorded questions as repeated measures in each condition: (Q1) “Do you have fun with this game?,” (Q2) “What is the score now?,” (Q3) “Do you like this game?,” and (Q4) “How much time is left?” We counterbalanced the order of the questions using a Balanced Latin Square design in each visualization condition. Each question was asked after the final visualization stage. The first question was designed to be asked 36 seconds after the game started, with a 45-second interval between each question’s start. In all conditions, the experimenter avoided any physical contact with the participants, including actions like tapping their shoulders, and also refrained from speaking themselves, as we had opted to use pre-recorded voices for the study.

4.2 Apparatus

We conducted the study on a two-seater couch in the lab. The couch has a seat size of 110 × 50 cm, with an interpersonal distance between the left and right seats of around 30 - 50 cm. Therefore, adequately representing an interaction in close space [18, 26]. Participants played the VR game on the couch while the experimenter played the seatmate on their left side, forming a side-by-side F-formation [27]. To ensure the controllability of the experiment, i.e., consistent seatmate orientations and corresponding visualizations between conditions and participants, we used the Wizard of Oz approach [8] by pre-recording the experimenter’s head orientation and visualization animation. Therefore, the experimenter was seated close to the participant to simulate a shared interaction scenario. During each social interaction in the VR game, the experimenter followed the study protocol, turning toward the user at specific timestamps without verbal communication and then turning away from the user to look straightforward. However, their real-time movements were not synchronized with and did not affect the visualizations in the VR game.

Next to the couch, we set up a Dell G5 laptop (GTX 2070) and ran Unity3D on an HTC VIVE Pro Eye VR headset (110° horizontal field-of-view). We used a single VIVE controller and integrated headphones for the VR interaction. In the task, we implemented the button using the trackpad on the controller to pause and resume the game. We connected an external loudspeaker to play the questions pre-recorded by the experimenter (seatmate). The loudspeaker was placed on the armrest of the couch close to the bystander’s side. We tested the volume of the loudspeaker and ensured they were loud enough to be heard in the VR game.

For the game, we referred to the popular VR game Beat Saber[4] and the open-source package Open Saber VR[5] to ensure engagement in the virtual world. The player’s goal is to hit as many cubes as possible at the right moment with a saber (controller) when cubes approach. Players can earn one point per cube if they succeed in hitting its colored sides and will lose one point if they miss it. We implemented effect sounds when participants successfully sliced the cubes. We used the same song as the rhythm background for each game and set a 240-second timer. We displayed the score and time on a top-front interface. When creating the seatmate visualizations, we resembled the experimenter’s virtual self and facial expressions for realistic social interactions. To create the animoji, we used Apple’s ARKit face tracking[6] on an iPhone to capture the facial expressions of the experimenter. To create the 3D avatar, we used the Ready Player Me application[7]. Then, we

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[4] https://beatsaber.com/, last accessed November 6, 2023

[5] https://github.com/dhcdht/OpenSaberVR, last accessed November 6, 2023

[6] https://developer.apple.com/documentation/arkit/content_anchors/tracking_and_visualizing_faces, last accessed November 6, 2023

[7] https://readyplayer.me, last accessed November 6, 2023

mapped the recorded facial expressions animations to the avatar's face using Unity Face capture package[8].

4.3 Measures

In each condition, we logged the reaction time to pause in the identification task and calculated the number of misses as a measure of system effectiveness. Additionally, we logged the task completion time, dwell time on visualizations, and head motion as measures of system efficiency. After each condition, we measured system satisfaction by self-ratings of social presence and bystander awareness, VR game experience, and user preferences. In particular, we measured the following dependent variables:

Misses: as the number and the proportion of failed tasks, i.e., did not pause the game, out of the total number of trials across all four conditions and within each condition. **Time to pause**: as the reaction time to detecting the seatmate's interest through the assigned visualization. **Task completion time**: as the time interval between pressing and releasing the button in the identification tasks in each condition. We used this quantitative measure to denote VR users' willingness to pause and interact with their seatmates until they switch back and resume the game. **Head motion**: as the measure of VR users' head movements switching between playing the VR game and viewing seatmate cues. We first measured the maximum angular movements along the yaw-axis, looking left (**min yaw**), and the pitch-axis, looking down (**min pitch**). The data was logged every 0.2 seconds and recorded as a maximum value that changes over time. In addition, we measured the angular velocity, i.e., average angular movements along the yaw (**yaw velocity**) and pitch (**pitch velocity**) axes over the total time in each condition. **Dwell time**: as the total time the VR users spent in areas of interest, shifting their attention from the game to the seatmate visualizations. **Game experience questionnaire (GEQ)**: After each condition, we used the five flow items from the core module using a 5-point Likert scale to capture users' engagement in the implemented game [20]. **Game Score**: We measured players' performance based on the number of cubes hit by the participant divided by the number of cubes generated during the entire game in each condition. **Social presence questionnaire**: We used the five-item social presence questionnaire on a 7-point Likert scale to capture users' feelings of being with another while seeing different seatmate visualizations in VR [2]. **Seatmate awareness, user preference, and physical discomfort**: We defined eight questions ourselves using a 5-point Likert scale to ask participants about their experiences regarding how easy it was to locate the seatmate, how much visual discomfort and neck fatigue they felt in VR, and how usable each condition was.

4.4 Procedure

After welcoming the participants, we explained the study goal of investigating close bystander awareness. After giving their informed consent for participation in our study, participants filled out a demographic questionnaire, and we invited them to sit on the couch with the experimenter on their left. In a slide show, we informed participants of the customized Beat Saber game, the designs of the seatmate's proxemic cues, and their tasks to identify the seatmate's (lack of) interest and give verbal answers. In a tutorial (around 8 minutes), they familiarized themselves with the VR headset and how to play, pause, and resume the game with the controller. We encouraged them to ask questions concerning the study task.

Next, the study started with the assigned visualization condition. Participants played the game on the two-seater couch, slicing as many cubes as possible. In between, they completed the identification task, i.e., answering four questions per condition, in VR without taking off the headset.

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[8] https://docs.unity3d.com/Packages/com.unity.live-capture@1.0, last accessed November 6, 2023

After each condition, participants were asked to fill out the questionnaires outside VR. We counterbalanced the order of the conditions using a Balanced Latin Square design [45].

After the last condition, we interviewed participants about their opinions and suggestions for game experiences and seatmate cues. Each participant was compensated 15 € for the study duration (1.5 hours). The study setup and procedure were approved by the local ethics review board.

4.5 Participants

We used convenience sampling to recruit 24 participants via our institutional mailing lists. We excluded the data of two participants as they did not follow the instructions at the beginning of the experiment and failed to pause and resume in the first one or two conditions. The remaining 22 participants (11 female, 10 male, and 1 non-binary) were between 19 and 38 years old ($M = 24.73$, $SD = 5.37$). Five participants had no prior VR experience, twelve use VR headsets less than once per year, four use VR weekly, and one uses it daily. Oculus and HTC VIVE were our participants' most commonly used headset models.

4.6 Data Processing

Our dataset consisted of recordings from 352 experimental trials (22 participants × 4 conditions × 4 questions). We processed the data and identified commission errors as the proportion of additional action, i.e., pausing the game twice. We attribute these errors to our study design's artifacts, as participants tend to react throughout the experiment when asked to complete the tasks. The mean rate of commission errors is 4.55% across all four conditions. The highest rate is 7.95% in the *Animoji* condition, when seeing the popup proxemic cues always within the view, followed by 4.55% in *Mixed*, 3.4% in *Baseline*, and the lowest 2.27% in *Avatar*. We corrected these errors by either deleting a quick 1.67-second ($SD = 1.31$) re-pause at the end or a 2.24-second ($SD = 2.26$) wrong pause at the start. In case two pauses are comparable, i.e., a 4.64-second ($SD = 2.23$) pause followed by a 4.38-second ($SD = 2.71$) re-pause, we deleted the time interval between them. Accordingly, we used the first pause to measure the time to pause and the time between the first pause and the last resume to measure task completion time.

5 RESULTS

We analyzed the processed data and, below, report our results regarding bystander awareness and experiences in the VR game.

5.1 Analysis

We used a one-way repeated measures ANOVA to analyze the effect of the VISUALIZATION factor. We tested the data for normality using Shapiro-Wilk's test. The analysis showed that all measures violated the normality (all $p \leq .033$) except the measure of social presence ($p = .338$) for simple parametric testing. Thus, for social presence, we used a t-test with Bonferroni correction applied. For all other measures, we applied non-parametric test procedures; we used Friedman and Wilcoxon signed-rank tests. Statistical significance is reported for $p < .05$.

5.2 Misses

The mean rate of misses is 7.67% across all four conditions. The highest rate is 15.9% within the *Baseline* condition when seeing no proxemic cues, followed by 11.36% in the *Avatar*, 3.41% in the *Animoji*, and 0% in the *Mixed* condition. On average, each participant had 0.64 misses in the *Baseline*, 0.45 in the *Avatar*, 0.14 in the *Animoji*, and 0 in the *Mixed* condition. The Friedman test showed no significant differences between all conditions, see Table 1. For missing data, we proceeded as follows: If the participant completed one or more trials in the given condition, we used the

Table 1. Means and standard deviation of the behavioral data and some questionnaire results, with statistical testing results. $^\triangle$ for social presence, we report the ANOVA results, F-statistics, and η^2. † the game did not pause; thus, this measure does not exist.

	Baseline		**Animoji**		**Avatar**		**Mixed**		**Friedman Test**			
Measure	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	χ^2	df	p	W
Misses [#]	.64	1.4	.14	.64	.45	1.22	0.0	0.0	6.77	3	.08	.103
Time to Pause [s]	n/a†	–	5.38	2.97	9.66	2.38	5.07	2.10	3.3	2	<.001	.688
Task Completion Time [s]	6.77	3.76	15.43	4.35	12.09	3.66	17.41	4.72	47.5	3	<.001	.72
Dwell Time [s]	n/a†	–	42.31	25.02	33.45	33.38	76.84	37.1	25.4	2	<.001	.576
Min Yaw (left) [deg]	56.8	28.01	55.81	31.72	66.47	25.02	81.97	18.10	19.5	3	<.001	.296
Min Pitch (down) [deg]	13.07	8.36	1.34	8.63	13.54	9.95	16.58	9.68	9.82	3	.02	.149
Yaw Velocity [deg/s]	5.4	2.78	4.74	2.82	7.05	3.33	8.05	2.64	16.5	3	<.001	.25
Pitch Velocity [deg/s]	3.72	1.45	3.09	1.19	3.32	1.12	3.57	1.58	1.7	3	.014	.162
GEQ-Flow	3.89	.76	3.72	.78	3.77	.75	3.73	.71	5.64	3	.13	.086
Game Score [%]	77.48	18.01	77.69	17.67	77.06	15.41	73.77	18.67	1.36	3	.714	.021
Social Presence	3.62	.71	4.34	.73	4.48	.69	4.54	.69	11.01$^\triangle$	3	<.001	.222
User Preference	2.27	.83	3.	1.15	3.	1.38	3.45	1.06	13.8	3	.003	.209
Visual Discomfort	1.45	.8	1.59	.96	1.64	.95	1.55	.8	2.71	3	.438	.041
Neck Fatigue	1.41	.59	1.41	.67	1.41	.73	1.45	.74	.529	3	.912	.001

aggregated mean value of these completed trials as the participant's behavioral data in the given visualization condition. If the participant failed all four trials in the given condition, we filled the missing data with the mean value of all completed trials by the other participants.

5.3 Behavioral Data

Figure 3 shows the frequency distribution of the mean timestamps of pause and resume.

5.3.1 Time to Pause. We discovered that the avatar introduced the longest time to identify the seatmate (see Figure 4 left). The Friedman test showed a significant effect of the VISUALIZATION factor ($\chi^2(3) = 30.3$, $p < .001$, $W = 0.688$). Post-hoc tests indicated a significantly longer time to pause in the *Avatar* condition than in the *Animoji* ($p < .001$) and *Mixed* ($p < .001$) conditions. The popup icons within the field of view introduced a faster reaction time than the situated avatar.

5.3.2 Task Completion Time. We found that participants spent the most prolonged pause in the game to detect any interest from the seatmate for conversation when viewing the continuous visualization (see Figure 4 middle). The analysis showed significant differences across conditions ($\chi^2(3) = 47.5$, $p < .001$, $W = 0.72$). Post-hoc tests showed significant differences between all conditions (all $p < .05$). Participants paused the game significantly longer to interact with the seatmate when receiving indications of the seatmate compared to no visual cues at all, especially viewing *Mixed* visualizations compared to the *Avatar* ($p < .001$), *Animoji* ($p = .045$), and *Baseline* ($p < .001$) conditions. Moreover, *Animoji* introduced a significantly longer pause for conversation with the seatmate than *Avatar* ($p = .003$).

5.3.3 Dwell Time. Likewise, the Friedman test showed a significant effect for the VISUALIZATION ($\chi^2(2) = 25.4$, $p < .001$, $W = 0.576$). Post-hoc tests confirmed significantly longer dwell time in the *Mixed* multi-representation condition than in the *Animoji* ($p < .001$) and *Avatar* ($p < .001$) uni-representation conditions (see Figure 4 right).

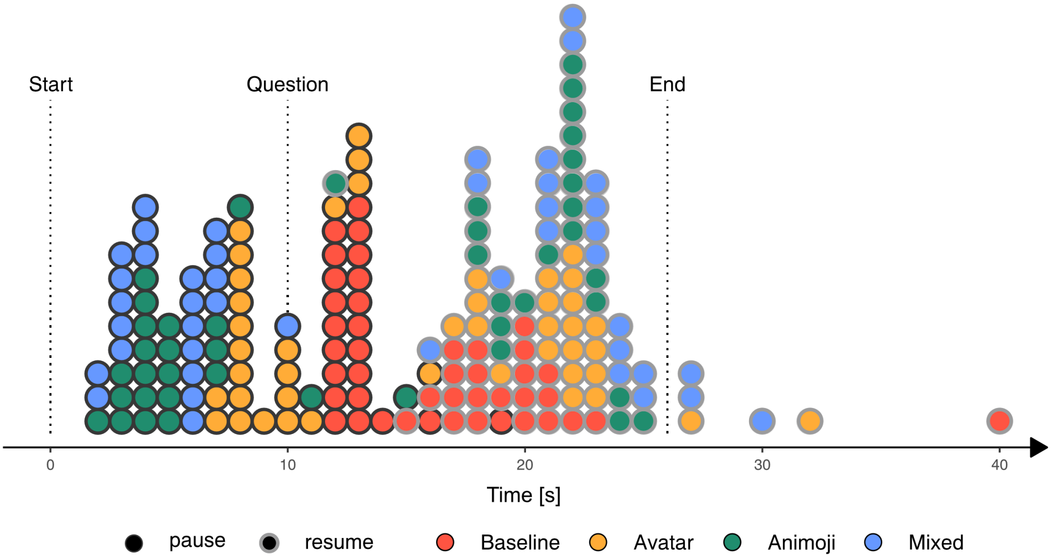

Fig. 3. Histogram showing frequency distributions of the 22 participants’ pause and resume timestamps in the identification tasks. We marked the moment the visualization started and was displayed to the participants, and around the pre-scripted 26 seconds afterward, the moment it ended and completely faded out. In between, we marked the question timestamp, the moment we played the pre-scripted audio questions, always around 10 seconds after the visualization started in each trial.

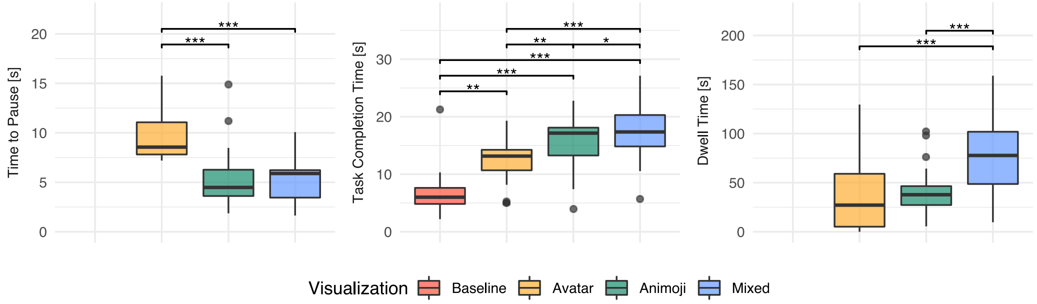

Fig. 4. Overview of the results for the time to pause, task completion time, and dwell time on the seatmate visualizations. * denotes $p < .05$, ** denotes $p < .01$, *** denotes $p < .001$.

5.3.4 Head Motion. We discovered that participants turned toward their seatmates wider and faster when viewing the seatmate’s continuous visualization. Visualization had a significant effect on the angle by which people turned left toward the seatmate ($\chi^2(3) = 19.5$, $p < .001$, $W = 0.296$), see Figure 5 left. Post-hoc tests revealed that in the *Mixed* condition, participants exhibited a larger maximum angular movement than in the *Animoji* ($p = .006$), *Avatar* ($p = .013$) and *Baseline* ($p < .001$) conditions. A similar pattern was found when looking at the downwards angular rotation on the pitch axis ($\chi^2(3) = 9.8$, $p = .02$, $W = 0.149$), see Figure 5 middle left. Post-hoc tests indicated that in the *Mixed* condition, participants tended to look further down than in the *Animoji* ($p = .003$)

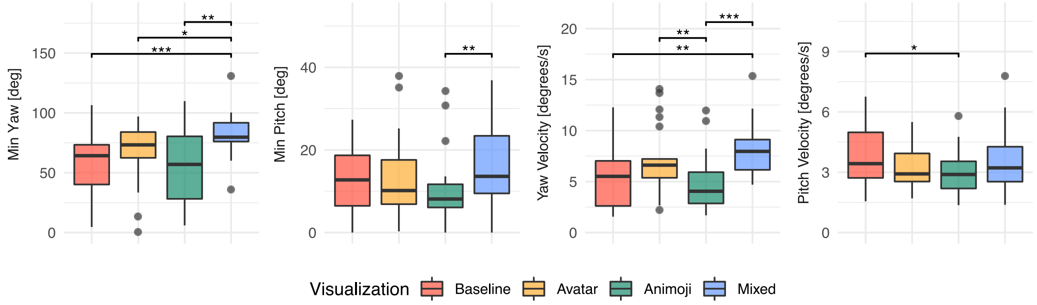

Fig. 5. Significant differences in the head motion data along the yaw axis, looking left and right, and the pitch axis looking up and down. * denotes $p < .05$, ** denotes $p < .01$, *** denotes $p < .001$.

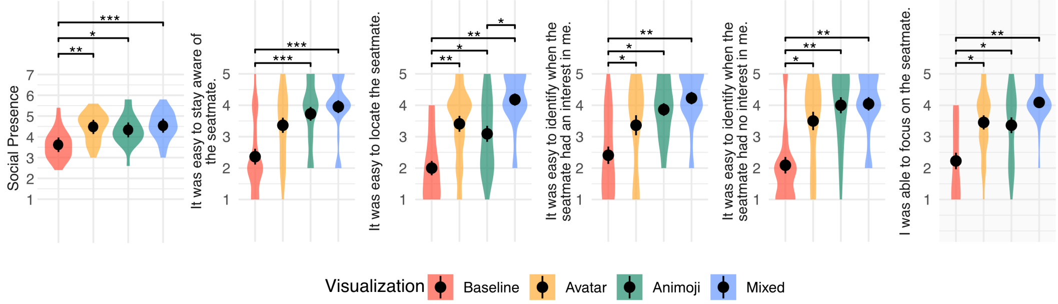

Fig. 6. The participants' answers to our self-defined questions regarding seatmate awareness and user preference in the experiment. * denotes $p < .05$, ** denotes $p < .01$, *** denotes $p < .001$.

condition, in which the separated 2D icons always appeared in the top-left corner of the users' view.

Additionally, the analysis showed a significant effect of the VISUALIZATION factor on the yaw velocity ($\chi^2(3) = 16.5$, $p < .001$, $W = 0.25$), see Figure 5 middle right. The post-hoc comparisons could show that there was significantly faster angular movement, looking left and right, in the *Mixed* ($p < .001$) and *Avatar* ($p = .008$) conditions than in the *Animoji* condition. Moreover, the *Mixed* condition introduced significantly faster yaw angular movements than the *Baseline* ($p = .004$). Further, the analysis showed significant differences in the pitch axis ($\chi^2(3) = 10.7$, $p = .014$, $W = 0.162$), see Figure 5 right. Post-hoc tests confirmed significantly slower pitch velocity (looking up and down) in the *Animoji* condition than in the *Baseline* ($p = .022$).

5.4 Social Presence

We analyzed the aggregated mean value of the 5-item social presence questionnaire. The one-way repeated measures ANOVA test showed a significant effect of VISUALIZATION on the overall social presence ($F(3, 63) = 11.01$, $p < .001$, $\eta^2 = 0.222$). Participants experienced a relatively higher "sense of being together with another" in the *Mixed* ($p < .001$), *Avatar* ($p = .002$), and *Animoji* ($p = .013$) conditions than in the *Baseline*, as indicated by post-hoc tests, see Figure 6.

Further, we analyzed the participants' answers to each item. When asked if the participants perceived that they were in the presence of another person in the room with them, the analysis showed significant differences across conditions ($\chi^2(3) = 9.45$, $p = .024$, $W = 0.143$). Post-hoc tests showed significantly higher approval for the *Mixed* condition than the *Baseline* ($p = .026$). When asked if the participants felt that the person was watching them and was aware of their presence, the analysis showed a significant ($\chi^2(3) = 21.2$, $p < .001$, $W = 0.321$) effect of the VISUALIZATION factor. Participants felt significantly more feedback from the seatmate when viewing the proxemic cues in the *Mixed* ($p < .001$) and *Animoji* ($p = .025$) conditions than in the *Baseline*, as revealed by the post-hoc comparisons. Finally, when asked if they perceived the person as being only a computerized image, not a real person, the analysis showed significant ($\chi^2(3) = 11.9$, $p = .008$, $W = 0.18$) differences across conditions. As shown in post-hoc tests, participants felt the seatmate significantly less like a real person when seeing the flat icon separated from the actual location in the *Animoji* ($p = .015$) condition than in the *Baseline*.

5.5 GEQ Flow and Game Score

We analyzed the aggregated mean value of the five flow items from the GEQ core module (see Table 1). The analysis did not indicate significant differences between conditions ($p = .13$). Likewise, we found no significant differences in each item across conditions when asking about participants’ concentration and engagement in the game, all $p \geq .102$. The game score mirrored these results. The analysis showed no significant differences between conditions ($p = .714$).

5.6 Questionnaire

After each condition, participants answered questions regarding their awareness of the seatmate and experiences in VR on a 5-point Likert scale (1: strongly disagree, 5: strongly agree), see Figure 6.

5.6.1 Seatmate Awareness. We asked the participants if it was easy to stay aware of the seatmate and found a significant effect of the VISUALIZATION factor on the ease of keeping seatmate awareness ($\chi^2(3) = 21.1$, $p < .001$, $W = 0.319$). Post-hoc tests confirmed significantly higher approval for the *Mixed* ($p = .006$) and *Animoji* ($p = .005$) conditions than for the *Baseline* condition. When we asked the participants if locating the seatmate was easy, it mirrored the results, with significant differences across conditions ($\chi^2(3) = 26.8$, $p < .001$, $W = 0.406$). Participants found it significantly easier to locate the seatmate in the *Mixed* ($p = .001$), Animoji ($p = .023$) and *Avatar* ($p = .008$) conditions than in the *Baseline*. Further, participants found it significantly easier to locate the seatmate using *Mixed* multi-representations than using the single *Animoji* ($p = .032$) as indicated by post-hoc tests.

Additionally, we asked the participants if it was easy to identify when the seatmate had a (no) interest in them. The analysis showed significant differences in identifying seatmate’s interest ($\chi^2(3) = 19.7$, $p < .001$, $W = 0.298$) and no interest ($\chi^2(3) = 24.5$, $p < .001$, $W = 0.371$). A similar pattern was found in post-hoc tests for the three visualization conditions that were significantly easier to identify both interests (*Mixed*: $p = .005$; *Animoji*: $p = .014$; *Avatar*: $p = .024$) and no interest (*Mixed*: $p = .002$; *Animoji*: $p = .003$; *Avatar*: $p = .028$), as compared to the *Baseline*. Likewise, the analysis showed significant ($\chi^2(3) = 21.9$, $p < .001$, $W = 0.332$) differences in the participants’ answers about if they were able to focus on the seatmate. Post-hoc tests depict significantly higher approval ratings for the *Mixed* ($p = .002$), *Animoji* ($p = .041$), and *Avatar* ($p = .013$) conditions than for the *Baseline*.

5.6.2 User Preference and Physical Discomfort. We asked the participants if they would like to use the system from day to day. The analysis showed significant differences in their ratings ($\chi^2(3) = 13.8$, $p = .003$, $W = 0.209$), see Table 1. Post-hoc tests indicated a significantly higher preference for the continuous visualizations of the seatmate in the *Mixed* ($p = .02$) condition than for the *Baseline*. Finally, we asked the participants if they felt general visual discomfort and neck fatigue during the

VR experience. The analysis did not indicate any significant differences across conditions in both ratings. Overall, participants reported limited to no physical discomfort using VR in the experiment.

5.7 Qualitative Results

In the final interview, we asked participants to describe why they liked or disliked a proxemic cue. We followed a thematic analysis [4] to code the participant's subjective comments. The identified themes are illustrated below with participants' representative quotes under their IDs. The authors translated all quotes from the participant's mother tongue to English.

For the most preferred *Mixed* condition, participants expressed that they liked that the visualization was continuous as it was *"obvious to identify whether the seatmate wanted to talk or not"* (P12) and *"easy to find the seatmate because the arrows pointed in the right direction"* (P10). With regard to following the proxemic cue of the seatmate in *Mixed*, P8 described the experience metaphorically as *"someone is knocking on the door, so you stop, listen, and turn around to see if someone is there."* However, some participants criticized such proactive guidance when they intended to immerse in VR, e.g., *"The arrows were a bit distracting. I felt like I had to stop the game and like some kind of obligation to look in that direction to focus on the person"* (P5).

In comparison, participants found the *Avatar* cues with the same arrow design less distracting, given its initial placement at the edge of the field of view in the headset, e.g., *"it was slightly on the left side. I felt the interruption was not intrusive"* (P17). As a result, some participants were too immersed in the game to notice the seatmate in time, e.g., *"When I looked there, the person looked already urgent"* (P12), or nearly missed as *"I feel that I have almost over-looked something from the person"* (P11). Additionally, we found mixed opinions about the visualization design. P1 found that the avatar body emulated the seatmate: *"when I saw the whole body of the 3D avatar, I remembered you (the experimenter) and felt like talking to a real person."* However, some found the 3D-model size *"so big"* (P9), especially with the situated placement, *"It is so close to me. That's why I was shocked the first time I saw it"* (P24).

In the *Animoji* condition, participants found the in-view icon *"was really easy to stay aware whether the bystander was looking at me or not"* (P12). Meanwhile, it lacked the arrow prompt, and thus participants expressed that it was challenging to find the seatmate's actual location, such as *"the notification had almost nothing to do with locating the bystander next to me, that was a completely separated thing"* (P6). As a result, an *Animoji* annoyed some participants who tried to find the other person and gradually ignored the actual location, e.g., *"I couldn't move my head to the bystander because the animoji followed me and was always in the top left"* (P7) and *"The animoji always stayed in the top left of my view. I just gave up trying to locate the bystander and talk into the room"* (P15). Moreover, participants disliked the flat animoji icons in the 3D virtual environment as *"it doesn't feel like a real person"*(P18), rather more like *"a programmed element in the game"* (P10), or *"FaceTime and a phone call, so I feel like no one is next to me"* (P3).

Finally, in the *Baseline*, participants mainly identified the seatmate's intention dependent on the verbal questions. Some participants found it *"less distracting"* (P24) and helpful to *"focus on the game"* (P11). Yet, when intending to interact with the seatmate, some missed the questions as they only heard *"the game was playing music"* (P2).

6 DISCUSSION

Our results reveal that using the in-view push notification to share orientation cues ensures fast and accurate bystander awareness in the confined side-by-side social setting. In contrast, the *Avatar* visualization that was pushed to the periphery of the view preserved social presence in VR but did not enable fast identification of the seatmate. Additionally, we discover that knowledge of the seatmate's location is essential for pleasant interactions even when the person remains unchanged in the same confined location. The *Animoji* effectively drew the user’s attention, but it was challenging for the user to locate the person. Moreover, our results indicate that combining push and pull notifications using smooth and continuous visualization techniques preserves engagement in VR experiences and allow for more pleasant social interactions. In particular, the *Mixed* visualization enabled users to notice the seatmate’s co-presence efficiently and directed them to the person’s actual location while maintaining the game flow and score comparable.

6.1 From Far- to Close-Space Bystander Visualizations

Our results show that adding visualizations of the seatmate allowed for more accurate identification with fewer misses on average, significantly increased social presence, and ease of maintaining seatmate awareness in VR, which aligns with the previous research on far-space bystander awareness [23, 37, 43]. In contrast, combining two visualization techniques that are both highly integrated into the virtual world seems to preserve game experiences without significant negative impact compared to the prior work using single or unlike visualizations [23, 31]. Thus, we suggest that adding bystander visualizations is important to ensure the system usability of VR experiences in confined social spaces.

Comparing our visualizations, we found a trade-off between facilitating social interaction and distraction from the primary task. When the system provided information on a change in seatmate orientation overtly in the player’s view (*Animoji* and *Mixed*), participants reacted faster. While the *Avatar* condition produced the longest reaction time to pause, along with the shortest task completion time and the shortest dwell time, it introduced efficient angular guidance to find the seatmate’s actual location. This indicates that it was hard to notice and stay aware of the *Avatar*, but once a need for interaction was registered, it was easy to find and talk to the seatmate. On the other hand, granular visualizations could benefit extended social interactions. We found the longest pause and focus on seatmate when viewing continuous visualizations (*Mixed*) that first grabbed the attention with the head-up icons and then directed users to the actual location through arrows as a guide. This longer interaction with the visualization also prompted participants to turn more and faster toward the seatmate than the *Animoji* condition. Therefore, guiding the user more granularly could enhance social interaction by facilitating a quicker transition from a side-by-side to a face-to-face arrangement [21]. Note that this angle of head motion was obviously confounded by the very design of the positioning in the visualization. Participants preferred the *Mixed* visualization as it provided the user with efficient orientation cues to initiate a conversation with the seatmate and effective proxemic cues to find the person’s actual location. Therefore, we recommend that VR systems leverage dynamic proxemic cues for optimal system usability when used in confined social spaces.

6.2 From Side-by-Side to Other F-Formations

Everyday close-space interactions entail a variety of physical spatial arrangements in which we use different proximity signals to communicate. When using VR in these everyday scenarios, spatial configurations range from side-by-side as in public passenger seats [46] to face-to-face and corner-to-corner, e.g., in shared social spaces [39, 40]. These different arrangements between VR users and bystanders involve dynamic dimensions of their proxemic relationship, influencing how they communicate with each other [22]. Specific arrangements even decrease the social acceptance of using VR on the go, like in face-to-face [40]. We envision a proxemic-aware system [31] to support interpersonal communication between VR and non-VR users in shared social spaces and enhance social acceptance of the technology [16, 30]. For example, in a face-to-face layout, the pitch *Orientation* gains importance when the seatmate looks upfront to signal interest. Likewise, in the corner-to-corner arrangement, the *Distance* or *Movement* can provide additional cues when the diagonal seatmate steps forward and waves to interrupt. These varying spatial settings of VR and non-VR users in restricted social spaces require additional validation of the proposed four-orientation-zone visualizations.

The placement of proxemic cues plays an important role in the system's new usability. We adjusted the initial position of *Avatar* from the actual location to the edge of the field of view in VR, expecting to support identification as previously confirmed when the bystanders showed up in front of users [23]. Still, the number of misses was higher than expected, as some participants could not react timely to the cues placed closer to the side yet far from the front game area. In contrast, extending the situated avatar forward to the head-up icons attached to the player's view (*Mixed*) satisfied both efficient identification and effective locating of the seatmate. From this, we learned that dynamic placements of bystander visualizations that compensate for the spatial shortcomings of the given physical arrangement are key to system effectiveness. Likewise, technical limitations influence the placement. A newer headset with a wider horizontal field of view might ease the identification of the side seatmate compared to our tested headset. To conclude, we recommend adding out-of-view bystanders first in the primary task view to ensure fast and accurate bystander awareness.

6.3 Limitations and Future Work

In this paper, we focused on the single-direction notification, supporting VR users' awareness of nearby non-VR users. Therefore, we did not implement the exact proxemic cues of the seatmate, e.g., based on the experimenter's real-time head tracking data, ensuring the experiment's controllability. We are convinced that our results contribute to a novel understanding of how continuous visualizations enable users to become aware of their dynamic proxemic relationships with nearby seatmates during VR experiences. However, our study design and results imply limitations and directions for future work, which we discuss below.

6.3.1 Extending and Beyond Visualizations. We only tested a one-to-one proxemic relationship, in which the *Mixed* system can offer several proxemic dimensions valid in the two-user setting while preserving game experiences to a certain extent (cf. GEQ Flow). However, in the F-formations with more than two users, revealing full details of all bystanders' proxemic cues and presenting the gathered data the same way without filtering can be distracting and break the presence in VR. Future work can further explore the diverse availability of proxemic cues from system-triggered snoozing of all proxemic cues [44] to user-triggered areas of social engagement [29]. Likewise, we only tested a single level of interaction interest. It is worth further investigating varying interest levels of the bystander in VR activities and additional exploration of visualization stages. For example, future studies can explore the nuance of visualization stages for indicating a bystander from showing passive interest, only observing without interacting, to active interest, immediate interaction demand. Besides, since we only used visual feedback to represent the proxemic changes of the person aside, we assume that additional auditory or haptic feedback [11] could increase bystander awareness more. Especially in verbal interactions between VR users and bystanders, adjusting in-VR audio improves users' auditory awareness so they can better converse with bystanders even at the cost of presence [35]. Future research is needed to test the use of multi-modal feedback considering user preferences.

6.3.2 Other Virtual Environments. We used a representative VR game to ensure engagement in the virtual world, requiring players to look in front constantly. Other games that require frequent head movements of the player might shorten or extend this reaction time, depending on the relative distance gap between the notification and game focus. Moreover, we expect other tasks that induce higher cognitive workload to prolong users' reaction time and further break engagement in virtual space. Future work needs to consider different VR tasks [38] when evaluating close bystander awareness, involving the *Orientation* changes in VR users and diverse cognitive workload.

6.3.3 From Unidirectional to Bidirectional Awareness. Finally, our pre-recorded orientation scripts ensured the experiment’s controllability while leaving the bystander’s real-time proxemic changes out of scope. Likewise, following the established research paradigm, our study design focused on unidirectional VR-user-centered notification [23] rather than bi-directional awareness between VR users and bystanders. Investigating bystanders’ awareness of VR users’ actions and intentions, prior work explored external user interfaces mounted outside headsets [5, 15, 17] or directly revealing VR users’ eyes towards those nearby, as the EyeSight function demonstrated in the Vision Pro by Apple[9]. Moreover, the bystander’s relationship with the VR user was found to have a stronger influence than the interpersonal setting on their comfort and acceptability of interruption strategy [34]. This emphasizes that there is still an under-explored dimension of proxemic relationships, *Identity*, being friends or strangers, as a potential direction for future work. To support bidirectional awareness, future work should investigate real-time interaction between VR users and bystanders and its causality in initiating interpersonal interaction when building proxemic-aware VR systems.

7 CONCLUSION

In this paper, we investigated how to support bystander awareness of VR users for close-space interactions during games based on the proxemic cues. We compared three seatmate visualizations using a 2D animoji, a fully-rendered avatar, and a combination. We found that the head-up *Animoji* efficiently grabs users’ attention to the seatmate but fails to support locating the partner during conversations. While the *Avatar* closely presents the seatmate’s location, users spend less time looking at them. In contrast, the *Mixed* continuous visualization was preferred by users, supporting fast identification of the seatmate’s presence, along with effective social interaction as it promotes easy locating, focusing, and identifying the seatmate’s intention. Engaging in immersive virtual environments with someone else is not optimal yet common when anticipating mobile VR interaction in confined social spaces across everyday contexts. Notably, using today’s VR headsets in these shared spaces challenges social acceptability and user adoption. On a broader view, our work underlines the vision of proxemic-aware VR to let users stay connected with co-present others, focusing on close bystander awareness, continuous visualizations, and dynamic physical spatial arrangements.

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