Workspace Guardian: Investigating Awareness of Personal Workspace Between Co-Located Augmented Reality Users

Bret Jackson, Linda Lor, and Brianna C. Heggeseth

Fig. 1: Workspace Guardians aim to promote awareness of personal workspace boundaries in shared spaces with multiple augmented reality users performing independent tasks. The scene above shows an example application where the AR user in the lower left must navigate a train station while avoiding encroaching on the virtual holograms of other users waiting for a train.

Abstract—As augmented reality (AR) systems proliferate and the technology gets smaller and less intrusive, we imagine a future where many AR users will interact in the same physical locations (e.g., in shared work places and public spaces). While previous research has explored AR collaboration in these spaces, our focus is on co-located but independent work. In this paper, we explore co-located AR user behavior and investigate techniques for promoting awareness of personal workspace boundaries. Specifically, we compare three techniques: showing all virtual content, visualizing bounding box outlines of content, and a self-defined workspace boundary. The findings suggest that a self-defined boundary led to significantly more personal workspace encroachments.

Index Terms—Mixed reality, augmented reality, three-dimensional displays.

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1 INTRODUCTION

For years, Augmented Reality (AR) and more generally Mixed Reality (MR) have captured people's imaginations with the promise of enhancing their experience of the world with superimposed digital imagery. Recent releases of head-mounted displays (HMDs) like the Microsoft HoloLens 2 [34], Magic Leap 2 [27], and the Apple Vision Pro [2], have brought this vision closer to reality. As we move closer to low-cost, comfortable, fashionable, every-day form-factors, AR HMDs have the potential for mass adoption and to become ubiquitous [4, 21]. Toward this end, research has progressed on AR's use in assembly training [50, 56], education [1, 60], gaming [44, 52], medicine [8, 14],

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visualization [25], Internet of Things [36], and many other application areas.

While these applications have tremendous potential, we emphasize that without a proper understanding of how AR co-exists with and supports human interactions, it will not thrive. In parallel with the exploration of new applications, researchers have attempted to address this barrier to adoption. Significant work has explored collaboration [49] between users, both in the same location [5] and remotely through telepresence [55].

However, one of the largest use-cases for ubiquitous AR in the distant future is for physically co-located users who are performing independent tasks rather than collaborative ones — consider how often we independently use our smartphones or laptops today in the same physical places as others. While some work has explored the limitations of mid-air gestural input in these situations [31] and others (e.g., [12, 28]) have explored the privacy implications of real-time sensors and image/video capture, relatively little has been done to explore the social norms of co-located but independent AR users.

Take for example our social norms with other forms of digital tech-

nology. It is quite common to see people who enter a meeting, presentation, or class late duck under the projection to not shadow the screen and block others' view. It is not yet clear what the analogous behavior is in AR with multiple co-located users that are each viewing their own virtual holograms. To establish these social norms, co-located AR users must become aware of the space being used by others for interacting with virtual content (See Figure 1).

We define this interaction space as the user's personal *workspace*, i.e., the area that is directly used for viewing and interacting with virtual content. This territory encompasses the placement of virtual artifacts and the movement of users interacting with them. Note that personal workspace is a more restrictive definition than proxemics (commonly referred to as personal space) which varies based on gender and age [19, 20, 54], motion [61], culture [16], familiarity [18], and attractiveness [23] between two people interacting.

Workspace territoriality has been previously explored in virtual environments [29] and on tabletop and vertical surfaces [48, 57]. Here, we explicitly explore situations where AR workspace territories are not bounded by physical objects. In these scenarios, communication and awareness of personal workspace boundaries is needed for negotiating shared space and avoiding intrusions.

In this paper, we explore visual techniques for communicating personal workspace boundaries between AR users, named *Workspace Guardians*. Three possible workspace guardians were designed and evaluated, representing a range of design possibilities for specifying boundaries and sharing private content. The findings show that: (1) users favor Workspace Guardians that are automatically defined based on their virtual content rather than being self-defined, (2) there is a trade-off between privacy and comfort which suggests adaptively modifying the amount of information communicated depending on task and environment, and (3) there is a need for more standardization around aligning AR coordinate spaces and communicating boundaries between different applications and HMDs from different vendors.

Our primary contributions are: identification of the need for communicating personal workspace boundaries between independent, co-located AR users; the creation of three workspace guardians; a comparative evaluation that provides insights into the different design factors (mode of creation and privacy vs. comfort) that may be used to promote awareness of personal workspaces to other users; and, identification of the need for more standardization for communication *between* AR platform software frameworks and toolkits. Our work can aid designers looking to provide awareness information for personal workspace boundaries.

2 RELATED WORK

2.1 Guardian Awareness Systems in Virtual Reality

Our work is inspired by guardian awareness systems for virtual reality (VR). These systems are designed to solve a different but related issue. Namely, providing safety to VR users by providing awareness of the physical world that is not visible to users wearing a VR HMD. In the AR context, the physical world is visible, but the digital content of other co-located users might not be. Here, the safety of users is less of a priority and the potential social implications of collisions with content become more important.

VR guardian systems can be classified into two categories. The first category contains systems that show safety boundaries of the physical environment (e.g., walls, furniture, and other objects). Magic Barrier Tape [10] defines safe walking spaces using virtual caution tape, allowing users to walk freely within the bounds and then virtually adjust the virtual vs. physical world alignment by pushing on the tape. Cirio et al. [11] developed a novel metaphor of a virtual bird companion that warns of impending collisions. Duval et al. [13] represent the limits of the physical environment using a blue grid, an approach adopted in commercial VR systems like the HTC Vive and Oculus headsets. This visual representation inspired the design of our Boundary Guardian.

Other VR guardian techniques like redirected walking [3] and ones balancing immersion with external awareness [24, 42] do not directly translate to AR. More closely related to our work are VR guardians that

provide context awareness for other co-located people — either also immersed in VR or non-HMD bystanders. Lacoche et al. [26] compared three awareness techniques — a cylindrical grid, ghost avatars, and a safe floor visualization — for understanding the physical positions of multiple VR users in a collaborative environment. The safe floor visualization was found to perform the worst because it required participants to focus on the floor rather than the task at hand. This informed our designs for Workspace Guardians to be defined volumetrically rather than simply being indicated with a floor outline. ShareSpace [59] allows bystanders to place shields within a physical room to provide input to the VR users about their location. Work by Wu et al. [58] is perhaps most closely related to our work. Rather than notifying VR users of bystander locations, they explore ways of making bystanders aware of the VR user's safety boundaries. Although the paper does not describe how the boundaries are specified, in practice, VR boundaries are based on specifying a safe space rather than a specific workspace. It is also not clear whether the findings apply when both users are using AR headsets rather than VR, motivating the work presented here.

2.2 Territoriality in Collaborative Contexts

Significant work has been done on collaboration between AR users. For an in-depth exploration see the survey by Sereno et al. [49]. Here, we present an overview of co-located or collaborative work focusing on establishing territoriality and personal workspaces.

In shared environments, people often divide the space into separate workspaces. On physical tabletops, Scott et al. [48] found that subdivided territory has both spatial properties (i.e., size, shape, and location) and functionality. They classified these as personal, group, and storage spaces. Personal workspaces are most often defined as the area along the table edge directly in front of users, which is consistent with other table-based workspace definitions [51].

Similar behavior extends to large digital displays. Wehbe et al. [57] analyzed territoriality in games on large display walls and found that users defined their workspace based on starting placement in front of the wall. Subsequent physical encroachment was found to be highly disruptive, although distant reaching into other's workspace was less disruptive. Cooperative games and tasks made the workspace boundaries more permeable. The level of disruption from physical encroachments motivates the need for workspace boundary awareness in AR. While the definition and management of these territories on tabletops and wall displays were constrained by the surface, in AR personal workspace can be more free-form.

Relatively little work explores free-form AR/VR territories. A notable exception is the work by Lee et al. [29] exploring territoriality in immersive VR environments for visualization tasks that found workspaces were defined by movement patterns and placement of artefacts within the environment. Once placed, participants followed social norms and did not interact with others' visualization objects outside of tightly-coupled collaboration. Definition of the workspace based on the virtual objects influenced the design of the guardian systems we tested because it is not yet clear what aspects (e.g., physical position/orientation, objects, self-defined outlines) are important for defining AR workspaces.

In AR, Medeiros et al. [32, 33] investigated confined workspaces of passenger transportation, but their findings relate to users' comfort levels with highly visible mid-air interactions that potentially encroach into others' personal space rather than how that space was defined or communicated.

Our work is further motivated by studies of security and privacy in shared AR spaces where participants have repeatedly expressed concerns over violations of personal space [28, 46, 47]. Lebeck et al.'s [28] findings provide a call to action that more work is needed on "defining personal space in AR, and determining how to best manage the personal spaces of multiple users who may cross paths". In this paper, we seek to address this call.

3 ASSESSING PERSONAL WORKSPACE AWARENESS NEEDS

To understand how co-located AR user awareness needs vary across interactions with other AR users, and what motivates these variations, we
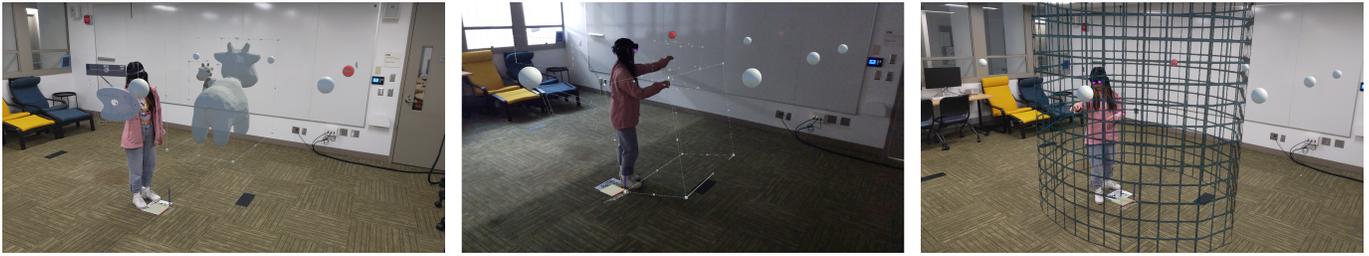
Fig. 2: Workspace guardian awareness techniques. These show the view of the Walker, not pictured, who was charged with working with the white and red spheres around the perimeter of the space. The spheres were always visible to the Colorer user. Left: full content view. Center: content outlines (lights were dimmed for figure clarity). Right: Self-defined boundary.

designed a study to investigate user encroachment into others' personal workspaces and evaluate user preferences. The following research objectives guided this work:

- **RO1: Automatic vs. Self-Defined Boundaries:** how the methods of defining boundaries and indicating them to other users impacts workspace encroachment.

- **RO2: Privacy Concerns:** how privacy considerations influence user preferences of workspace guardian techniques.

3.1 Workspace Guardian Awareness Techniques

Based on these research questions, we designed three visual techniques for providing awareness of personal workspace boundaries to other users. Called *Workspace Guardians* after the guardian systems that prevent collisions in VR, these techniques present different types of visual feedback to co-located AR users. Although there are many potential options for workspace guardians, the specific guardians implemented here attempt to sample the possible design space of the research objectives. For RO1, the full content view and content outline guardians are automatically defined compared against the self-defined boundary guardian. For RO2, the self-defined boundary guardian, content outline guardian, and full content view guardian, progressively sample from full content privacy, intermediate privacy, and no privacy options, respectively.

3.1.1 Full Content View Guardian

The full content view guardian (shown in Figure 2 left) presents all of the virtual content of a user to other users. This visual feedback provides no privacy protection and is automatically determined by the spatial positions of the virtual holograms. Although a user can see another user's content and interactions with it, they cannot themselves interact with the other user's content. This aims to preserve psychological ownership over one's body and virtual belongings, while still providing spatial awareness of them.

3.1.2 Content Outlines Guardian

The content outlines guardian explores increased privacy compared to the full view, while still being automatically defined by the spatial positions of the virtual content. Shown in Figure 2 center, the content outline guardian displays the bounding-box outlines of the virtual holograms. The outlines resize, reorient, and reposition automatically as the owning AR user manipulates the underlying content.

3.1.3 Self-Defined Boundary Guardian

The boundary guardian (see Figure 2 right) provides maximum content privacy and self-definition. The user defines their personal workspace by drawing a boundary shape on the floor around themselves. Inspired by the VR guardian systems on popular VR head-mounted displays, the drawn shape is extruded into a transparent grid surrounding the user. The grid is visible both to the workspace owner and bystanders, but bystanders are not able to see any details of the owner's virtual content.

3.2 Methodology

The experiment used a within-subject design with an independent variable of workspace guardian technique. Pairs of participants were recruited, and each experienced all techniques. The order was fully counter-balanced to avoid learning and order effects.

We did not include a baseline condition of having no guardian. Prior work in VR guardian systems [58] found that excluding guardian awareness techniques led to significantly more physical collisions with unseen objects and bystanders. Furthermore, since we cannot avoid virtual content that we do not know exists, we would not be able to establish social norms around encroaching on personal workspace without any workspace guardian.

To emulate a shared working or public setting, each participant within the pair was given an independent task in the shared physical space. Participants kept the same task for each of the three technique conditions. One participant was given a stationary task. The other participant was given a task that required them to actively move throughout the entire space. This represents a scenario where individual tasks could be disruptive to each other, with the active user potentially encroaching on the stationary participant's personal workspace. This also models many common use cases for co-located but non-collaborative AR. For example, the stationary user might represent someone browsing their email and the Internet in multiple virtual windows while waiting for a bus on the sidewalk. The active user might represent someone walking down the sidewalk using AR for navigation and directions, as in Figure 1.

3.2.1 Tasks

Independent tasks were assigned to participants because if participants are working on a collaborative task, then their personal workspaces would likely be shared rather than independently defined. The tasks were assigned randomly within the pairs of participants.

The stationary user was assigned the task of painting the surface of a virtual three-dimensional (3D) model of a cow. Shown in Figure 3, a smaller copy of the model was presented already painted, and participants were asked to either replicate its coloring on the larger model or design their own color scheme. This task was chosen to provide feelings of ownership over the virtual content because it was based on the user's own creative output [45]. Throughout the rest of the paper, the user with this task will be referred to as the Colorer.

Virtual paint brushes follow the Colorer's index fingers, and they could paint with either hand by bringing a brush within 5cm of the model surface. An artist's palette could be used to change the paint color by placing the brush within different colored 'paint' spheres. Color selection was indicated by an auditory confirmation and visible update to the paint color shown on each paintbrush tip. A floating menu panel with a slider was used to change the size of the paint mark that was transferred to the model surface.

Each of the virtual holograms (main cow model, goal reference model, color palette, and brush size menu) could be independently scaled, rotated, and translated either by pinching the thumb and index fingers on both hands and moving the hands relative to each other or by selecting a manipulation handle on the bounding box control outlines
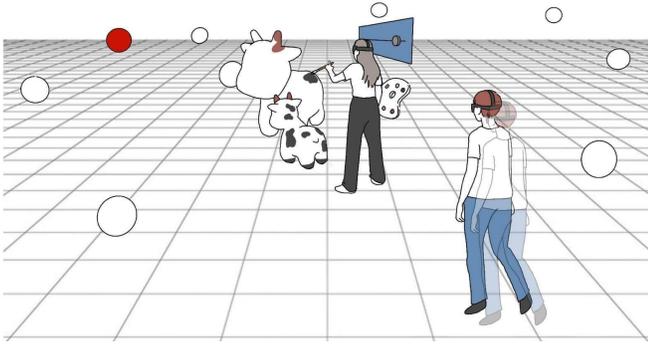
Fig. 3: The study task. The stationary Colorer (shown center) paints a 3D model, while the Walker (figure in lower right) navigates around the Colorer's personal workspace to select the red colored sphere. The Workspace Guardian shown is the Full Content View.

that appear based on hand proximity.

The active user was assigned a search-and-find task. Throughout the paper we will refer to this user as the Walker. Eight small spheres were distributed within the bounds of the experiment space at 1.5m off the floor. The goal of the task was to search for a specific sphere that was colored red. The remaining spheres were colored white. The Walker was instructed to move to the sphere and touch it to confirm that it was found. Then another sphere would turn red and the process was repeated until all the spheres had turned red twice and the technique condition would automatically end. In all conditions, the spheres were visible to the Colorer.

To generate the sphere positions, candidate points were generated within a 4.572×4.572 meter square to provide a small buffer on each edge of the experiment space so that no spheres would be too close to a wall to select. The candidate points were generated through Poisson disk sampling [7] with 1m spacing. Points within 1.5m of the Colorer (stationary at the center of the experiment space) were removed to prevent spheres initially appearing directly within the Colorer's virtual content. We also required that the shortest walking path between spheres in the order that they turn red frequently crossed over the Colorer's workspace to allow for possible encroachment; for example, a red sphere could be directly across from the previously red sphere, providing an opportunity for the Walker to walk through the Colorer's workspace or around it.

From the candidate points, subsets of 8 points were repeatedly chosen at random until 4 sets (one for training and the three conditions) were obtained where at least 75 percent of the paths crossed within a 1.5m radius around the Colorer's center position. Other than the training set which was consistent for all participant pairs, the other three sphere position sets were counterbalanced across technique conditions so that all sets were used for each condition and in every possible ordering.

3.2.2 Apparatus and Implementation

The experiment was run using two Microsoft Hololens 2 [34] AR head-mounted displays (HMDs). Software was implemented in Unity3D [53] with the Mixed Reality OpenXR plugin and the Mixed Reality Toolkit (MRTK2). Although the applications could run natively on the HMDs, to facilitate networking, the applications were executed on two desktop computers with the input/output streamed to the HMDs using the Microsoft Holographic Remoting application. The HMD for the Colorer task streamed from a 4.4GHz PC running Windows with dual NVidia GTX1070 GPUs, and the Walker HMD streamed from a dual 3.5GHz processor PC running Windows with three NVidia Quadro P5000 GPUs.

The implementation of the Colorer's painting task uses ray-casting to determine the closest point on the 3D model to the user's index finger tip. If the distance between the finger and the surface is within the activation distance (5 cm), a circle of color is transferred to the model.

The system uses a rendering pass where the fragment shader renders to the UV space of the 3D mesh texture. The graphics rasterizer then creates triangles out of the vertex coordinates converting them to UV texture positions. This effectively recreates an unwrapped texture map of UV islands. Then during rendering, the UV coordinate corresponding to the closest paintbrush point is passed into the fragment shader. Signed distance calculations are performed per fragment in UV space to this coordinate and fragments within the brush size radius are output with the paint color. This writes directly to the texture that is then applied to the model and effectively uses the GPU parallelism to speed computation.

For the boundary guardian, the implementation again uses ray-casting to draw the boundary. The drawing mode is activated by the Colorer saying "Draw boundary". Pinching the thumb and index finger starts recording boundary points based on the intersection between a ray and the floor. The ray is created with an origin point half-way between the user's wrist and their shoulder position (estimated based on the head position of the HMD) extending through the finger pinch position. This has the effect of making the ray responsive to wrist and arm movements, while minimizing jitter that would be exacerbated down the length of the ray. Jitter was further minimized by filtering the ray origin and direction using the 1€ filter [9]. Once the Colorer indicates satisfaction with the drawn boundary outline by saying "Finish boundary", the outline is closed by reconnecting the end point to the start. The shape is then simplified by taking the convex hull of the drawn points.

The Walker's task implementation is simpler than the Colorer's task. As mentioned previously the sphere positions were randomly generated and read into the system from a configuration file. Unity3D physics colliders were added to detect when the red sphere was touched.

The experiment and workspace guardians require a consistent coordinate system between HMDs to display the virtual content in the same positions and orientations for both participants. Each Hololens defines its own coordinate system based on spatial mapping, so a common system was implemented by detecting a QR code taped to the center of the experiment space. Virtual content and recorded positions were set relative to this common marker.

Unity's Netcode for GameObject library was used to network the two headsets. Application state was synchronized through Network-Transform components and custom client and server remote procedure calls (RPCs).

3.2.3 Participants

For the study, 18 pairs, 36 total participants (self-identified as 10 female, 22 male, 4 other), were recruited through social media and mailing lists. Ages ranged from 18–35 (Mean = 21.9, SD = 4.31).

Thirteen participants reported never using AR or VR previously. Fifteen reported using AR or VR 1–5 times, two reported 5–20 times, and six reported more than 20 prior uses. Five reported having no prior video game experience, eleven reported monthly video game use, eight reported weekly use, and twelve reported daily use. All participants with more than five prior AR or VR experiences reported weekly or daily video game use, and all were less than 22 years old.

Because our use case of co-located AR users may involve friends or strangers, we allowed participants to sign up either as pairs or individuals to preserve ecological validity. Those signing up as individuals were randomly paired together. Participants were asked whether they had previously met, and to describe their previous relationship to the other participant in their pair. Based on these responses, we categorized the pairs into four categories: strangers (n=5), acquaintances with knowledge of each other but limited interaction (n=3), friends (n=8), and partners (n=2).

3.2.4 Procedure

After providing informed consent, the participants were introduced to the study and assigned tasks. Both participants performed the built-in Hololens 2 calibration procedure to calibrate the eye-tracking, hologram alignment, and hand tracking. Participants trained in their respective tasks in the same room but without any guardians or visual feedback

about what the other participant was doing so as not to bias future conditions. The participants were given an unlimited amount of time to train, but most trainings took less than 15 minutes. In the training process, the Colorer was instructed in how the painting interface works and was prompted to practice manipulating the virtual holograms scale, positions, and orientations. Following this, they were instructed on the process for drawing the boundary of their personal workspace. They were able to redraw the boundary until they were satisfied it accurately represented their personal workspace. During the boundary drawing, the virtual content (cow model, reference model, color palette, and brush size menu) continued to be shown to the Colorer. The Walker was instructed on how to complete the task and asked to practice until they felt comfortable with it.

After training, the participants were asked to complete their tasks for each guardian condition. After each condition was tested, each participant was asked to complete a survey about their experience with the condition. They were also able to rest briefly if they chose. At the end of all conditions, a summative survey was given and demographics were collected on the participants and their relationship to each other. The whole experiment lasted about 30 minutes governed by the time it took the Walker to complete their task.

3.2.5 Metrics

The dependent measures are the number of collisions between the Walker's head or hands (calculated using physics colliders attached to the Colorer's virtual content), the spatial invasion rate, and the temporal invasion rate. Similar to Wu et al. [58], for the Full Content View and Outlines Guardians, we define the spatial invasion rate as the distance Walkers moved while colliding with the Colorer's virtual content divided by the total distance they traveled in each trial. For the Boundary Guardian, the distance was recorded while they were within the Colorer's self-defined boundary. The temporal invasion rate is defined as the amount of time spent colliding or within the boundary over the total task completion time. After each condition, participants completed the Simulator Sickness Questionnaire (SSQ) [22] and a questionnaire about the experience, consisting of statements for rated agreement on a five-point Likert scale. The questions are summarized in Figure 7.

3.3 Results

We calculated average collisions, spatial invasion rate, and temporal invasion rate for each condition across participants. To compare conditions, we report an interval estimate of the mean differences within subjects for pairs of our three guardian types to show effect sizes and the p-values from two-sided Wilcoxon signed rank tests.

3.3.1 Collisions

Figure 4(a and b) summarizes the mean collisions between the Walker's head and hands with the Colorer's virtual content. Error bars show 95% confidence intervals. Figure 4(c and d) show Bonferroni-corrected average within subject differences. The analysis of the within subject differences shows that, for both head and hands, there is evidence that both the Full View and Content Outlines Guardians have significantly fewer collisions than the Boundary Guardian (Full View Head: Z = 116, p = 0.001; Full View Hands: Z = 150.5, p < 0.001; Content Outlines Head: Z = 104, p = 0.001; Content Outlines Hands: Z = 171, p < 0.001). There was no evidence of a significant difference between the Full View and Content Outlines in terms of number of collisions (Head: Z = 2.5, p = 0.11; Hands: Z = 36, p = 0.10).

3.3.2 Spatial Invasion Rate

The mean values and within subject comparisons of spatial invasion rate are shown in Figure 5. Within subject comparisons reveal that the Boundary Guardian has significantly higher spatial invasion rates than Content Outline or Full View (Content Outline: Z = 103, p = 0.001; Full View: Z = 116, p = 0.001). There was no evidence to suggest that the spatial invasion rate differed between the automatically defined (Full View and Content Outline) Guardians (Z = 10, p = 0.29).
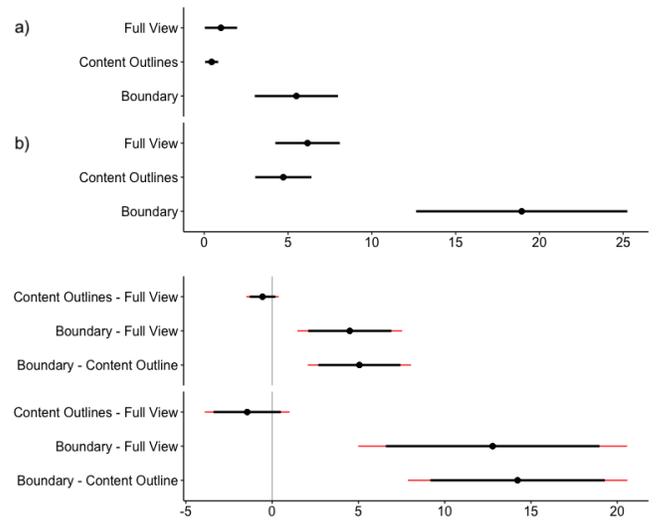

Fig. 4: Collisions with virtual content for the Walker's (a) head and (b) hands; mean collisions with 95% CIs (top), corresponding within subject comparisons between the guardian types (bottom). Error bars: 95% CIs. Red bars: CIs for Bonferroni-corrected within subject comparison.
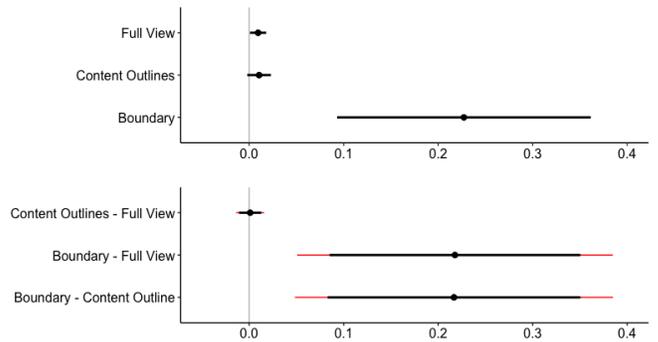

Fig. 5: Spatial Invasion Rate by guardian type (top); (bottom) corresponding within subject comparisons between the guardian types. Error bars: 95% CIs. Red bars: CIs for Bonferroni-corrected within subject comparison.

3.3.3 Temporal Invasion Rate

Figure 6 presents the mean temporal invasion rates and within subject comparisons between guardian types. Similar to the spatial invasion rate, within subject comparisons reveal that the Boundary Guardian has significantly higher temporal invasion rates than both of the automatically defined Guardians on average (Content Outline: Z = 103, p = 0.001; Full View: Z = 116, p = 0.001).

3.3.4 Simulator Sickness Questionnaire

The SSQ [22] was used to determine whether any of the guardian conditions impacted participants' well-being. Sub-scores and total simulator sickness were calculated using the standard formulas with the inclusion of the bracket notation missing in the total score computation presented by Kennedy et al. (See Bimberg et al. [6]). The mean and standard deviations are summarized in Table 1. There were no significant differences in total simulator sickness scores. All means, medians, and interquartile ranges were below the commonly held threshold of 20 indicating a "bad" simulator.

3.3.5 Qualitative Results

Between completing conditions, participants completed a survey using 5-point Likert scales related to: (1) comfort with the Walker moving
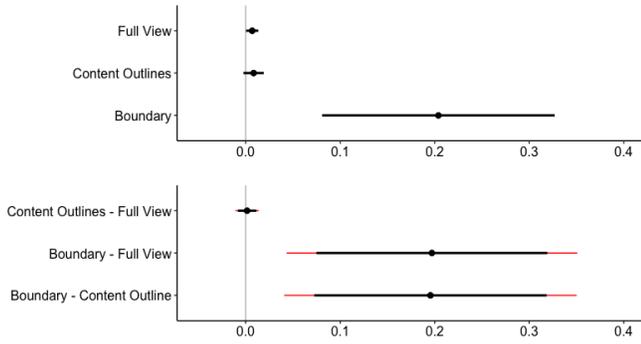
Fig. 6: Temporal Invasion Rate by guardian type (top); (bottom) corresponding within subject comparisons between the guardian types. Error bars: 95% CIs. Red bars: CIs for Bonferroni-corrected within subject comparison.

Table 1: Mean Simulator Sickness Questionnaire (SSQ) sub-scores. Standard deviation shown in parentheses.

Guardian	Task	Nausea	Oculomotor Disturbance	Disorientation	Total Simulator Sickness
Full View	Walker	6.89 (13.4)	15.6 (25.0)	17.8 (28.2)	15.2 (24.5)
	Colorer	6.89 (13.0)	14.7 (20.9)	8.51 (14.4)	12.3 (18.0)
Outlines	Walker	6.89 (13.0)	11.4 (15.9)	14.7 (22.6)	12.3 (18.0)
	Colorer	6.89 (10.2)	13.1 (14.9)	6.96 (10.9)	11.0 (13.0)
Boundary	Walker	6.36 (9.82)	10.5 (13.8)	9.28 (13.5)	10.2 (13.6)
	Colorer	6.36 (9.26)	12.6 (14.0)	6.96 (11.9)	10.6 (12.3)

around the room, (2) feeling safe, (3) ability to concentrate on the task, (4) whether the task was interrupted by the other participant, (5) their ability to perceive their position relative to others in the room, (6) whether the Colorer used a reasonable amount of space, and (7) whether their interactions were directed by what they could see of the other participant's AR projections. The survey results are summarized in Figure 7. Overall, almost all participants felt safe and all walkers understood the bounds of the personal workspaces.

We compared the Likert responses using a series of two-sided Wilcoxon signed rank tests to compare the responses between Colorer and Walker within the participant pair and two-sided Wilcoxon rank sum tests to compare the groups. We note significant differences in the understanding of the bounds of the workspace (signed rank: Z = 23.5, p = 0.002, rank sum: Z = 1094, p = 0.005) and whether the interactions were direct by the other's AR projections (signed rank: Z = 41, p < 0.001, rank sum: Z = 733, p < 0.001).

Similarly, we compared responses by Guardian condition and noted significant differences in comfort (signed rank: Z = 3.5, p = 0.04; rank sum: Z = 550, p = 0.165) and ability to concentrate (signed rank: Z = 20.5, p = 0.04; rank sum: Z = 552.5, p = 0.22) between Full View and Outlines, the amount of space used was reasonable between Boundary and both automatically defined Guardians (Full View - signed rank: Z = 84, p = 0.01; rank sum: Z = 784, p = 0.08; Content Outline - signed rank: Z = 21, p = 0.03; rank sum: Z = 497, p = 0.05), and the comfort between Outlines and Boundary (signed rank: Z = 0, p = 0.003, rank sum: Z = 472, p = 0.02).

Note, that the indications of higher disagreement for whether the Colorer was directed by what they could see of the Walker's projections is expected because the Colorer was stationary and their task was completely independent of the Walker's spheres unless they scaled their projections enough to intersect a sphere.

At the end of the experiment, participants ranked their preference for the different guardian conditions. The ranking is shown in Figure 8. For participants with the walking task, there was a clear preference for the Full View Guardian followed by the Content Outlines Guardian (χ^2 = 22, p < 0.001). The self-defined Boundary Guardian was the least preferred. For the Colorer, there were no strong preferences for the most preferred guardian, although when combining first and second choices the Content Outlines Guardian was preferred over the other
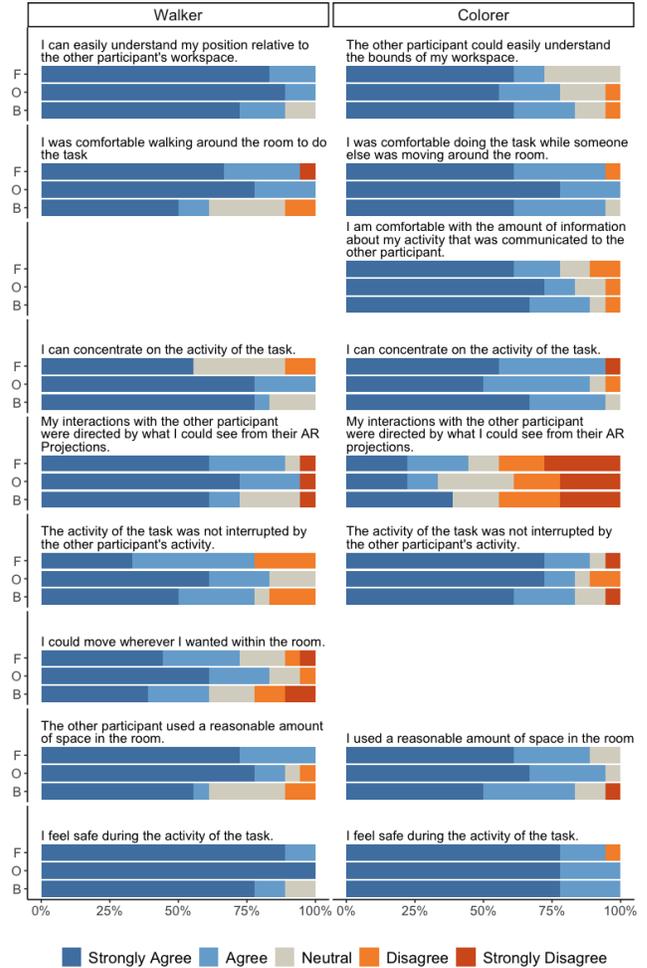

Fig. 7: Qualitative results by guardian condition and task. Participants rated on a 5-point Likert scale from Strongly Disagree (1) to Strongly Agree (5). F represents full view guardian, O represents just Outlines, and B represents the Boundary Guardian.

two options.

Participants also ranked the importance of different aspects that might influence the design of workspace guardians. The aspect rankings are shown in Table 2. Other than prevention of physical collisions which the majority of both types of task participants ranked first, the rankings between Walkers and Colorers are inverted.

4 DISCUSSION AND DESIGN IMPLICATIONS

The first finding is that all of the workspace guardian techniques studied influenced the participants' walking paths in an effort to avoid the Colorer's workspace. Note the predominately elliptical paths (shown in Figure 9) that participants took rather than walking straight across the space. This suggests that similarly to the physical world, when made aware of workspace boundaries people will try to avoid encroaching on them.

4.1 Favor Automatic Creation of Guardians

There are several findings related to the research objectives described in section 3. For *R01: Automatic vs. Self-Defined Boundaries*, the automatically defined guardians (full view and content outlines) had fewer collisions and lower spatial and temporal invasion rates compared to the self-defined boundary condition. This is consistent with a strong preference by Walkers and a slightly weaker preference by Colorers for automatically defined boundaries.

Table 2: Importance ranking counts for design aspects (1: Most Important, 5: Least Important). Red lines show relative differences between participants by task.

| Walker							Colorer						
Aspect	1st	2nd	3rd	4th	5th	Avg Rank	Aspect	1st	2nd	3rd	4th	5th	Avg Rank
Prevention of physical collisions	11	2	1	2	1	1.72	Prevention of physical collisions	13	2	2	1	0	1.50
Being able to view what others are doing in AR	4	4	2	5	3	2.94	Privacy of personal content from neighboring users	2	6	3	5	2	2.94
Self-defined boundaries	2	4	7	3	3	3.22	Prevention of collisions with AR projections	1	4	6	7	0	3.06
Privacy of personal content from neighboring users	1	5	4	3	5	3.33	Self-defined boundaries	2	4	4	5	3	3.17
Prevention of collisions with AR projections	0	3	4	5	6	3.78	Being able to view what others are doing in AR	0	2	3	0	13	4.33
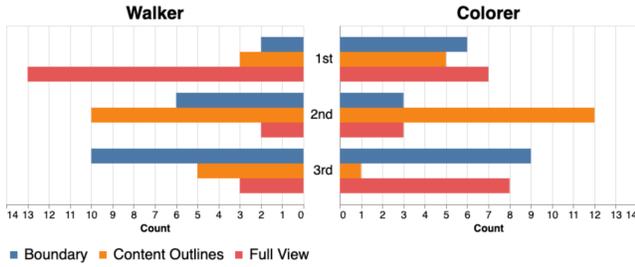
Fig. 8: Ranked guardian preference by task.

These findings are likely a result of Colorers often self-defining workspace boundaries that were larger than needed to contain their virtual content. One of the participants commented on this specifically: *"The boundary was significantly larger and harder to avoid than simply seeing the full objects which were much smaller than the boundary area and I could walk around easier".*

The visual representation of self-drawn boundaries likely also had an effect on preference. Participants rated this condition less favorably in terms of comfort. The Boundary Guardian was designed to be visually similar to common commercial VR guardian systems with a large wire-mesh indicating the boundary. Thus, it is more visually obvious when participants were encroaching on it: *"Boundary view was least preferred because I became more aware of the AR boundary and real life boundary and I didn't want to disturb the other person's task."* Similarly, the larger visual presence may have been perceived differently: *"I preferred the content outlines option over the boundary option because it felt like there was much more space to move around in even though the boundary option never felt like it took up too much space".* Based on these findings, we recommend that future workspace guardian designs focus on automatic definition. If not based directly on the virtual content, the visual impact of the guardian should be considered.

4.2 Tension Between Privacy and Comfort

The Boundary and Content Outline Guardians were designed to explore *R02: Privacy Concerns*. Both of these conditions did not directly show co-located users the full virtual content. Participants' opinions on privacy differed depending on their assigned task. Walkers had a strong preference for the Full View Guardian, and they generally rated the aspect of viewing what others are doing in AR highly and privacy of personal content less highly in term of importance (Table 2). Colorers rated these aspects inversely, despite one Colorer participant remarking that coloring a model does not share much sensitive information.

Examining the qualitative feedback from Walkers provides more insight. When asked to explain their ranking of the guardians, many responded that they were curious about what the Colorer was doing. This curiosity extended to knowing not just whether they were encroaching on the personal workspace of the other participant, but whether that encroachment would be an issue. One participant commented *"With the full view I felt like I understood what the other participant was doing and knew if/why I would be a bother in his space".* This was echoed by another participant too: *"Seeing the boundary of the other participant made me want to avoid their boundary in all together and being able*

to see what the participant is doing made me more comfort [sic] to move around.". These responses suggest that automatically created guardians, based only on the outlines of the the virtual holograms do not always convey enough information about how a user is interacting with them within their workspace. Future research in AR workspace awareness techniques should explore this in more detail. For example, integrating eye and hand tracking data to provide visual feedback on the interaction regions within outlines with might lead to better results while still maintaining privacy in applications where it is required.

Beyond not being practical for privacy reasons in public settings or when viewing sensitive data, the Full View Guardian has a couple of other disadvantages. First, participants sometimes found it distracting to view the full content of the other participant. This is reflected in the Walker's increase in disagreement Likert values when rating whether they were able to concentrate on the task in the full view compared with the other two guardian conditions. Several participants commented on this as well: *"I was able to concentrate more on my task if I couldn't see what my partner was doing."* and *"Because it [the boundary] would make it simpler and less distracting for me as a user".* The Content Outline Guardian was found to be a good compromise between privacy and distraction: *"I found the content outlines to be the happy medium between enough information but not distracting".* Prior work [29] has found similar trade-offs between users wanting more awareness of personal workspaces but being distracted by the additional information.

The second disadvantage for the Full View Guardian is the performance impact. In this study the task implementations were simple enough that rendering performance was not an issue; however, in dense public settings with many co-located AR users, faithfully replicating content between HMDs would be performance prohibitive.

4.3 A Need for Standardization

Even for the visually simpler AR workspace guardians, more standardization is needed to be able communicate guardian information between headsets. This includes protocols for specifying the workspace extents, but also for positioning within a consistent coordinate space. The QR code approach used in this study is not practical in the wild. Other solutions for placing objects with a persistent world position like Microsoft Azure Spatial Anchors, Meta Shared Spatial Anchors, and Apple ARKit ARAnchors are tied to specific vendors and often specific multi-player applications. There is some work toward this end (e.g. [30]), but crucially, these techniques must work *between* multiple different brands of HMDs and different applications to be viable in a public setting where there are no prior conditions on the technology or applications of users.

5 LIMITATIONS AND FUTURE WORK

The use of a lab study was necessary for controlled examination of the awareness techniques, but the practical limitations of participant time limits our findings. Future work should evaluate across a broader range of potential activities, interactions, and environmental contexts as these situational factors influence awareness needs [38, 39].

The specific design choices for the three example workspace guardians were informed through iterative development and the need to cover the possible design space of the research objectives. Future work could explore alternative visual designs and integration of haptics or auditory systems which have been found to promote awareness within VR physical boundary guardians [15, 41]. Additional work could explore
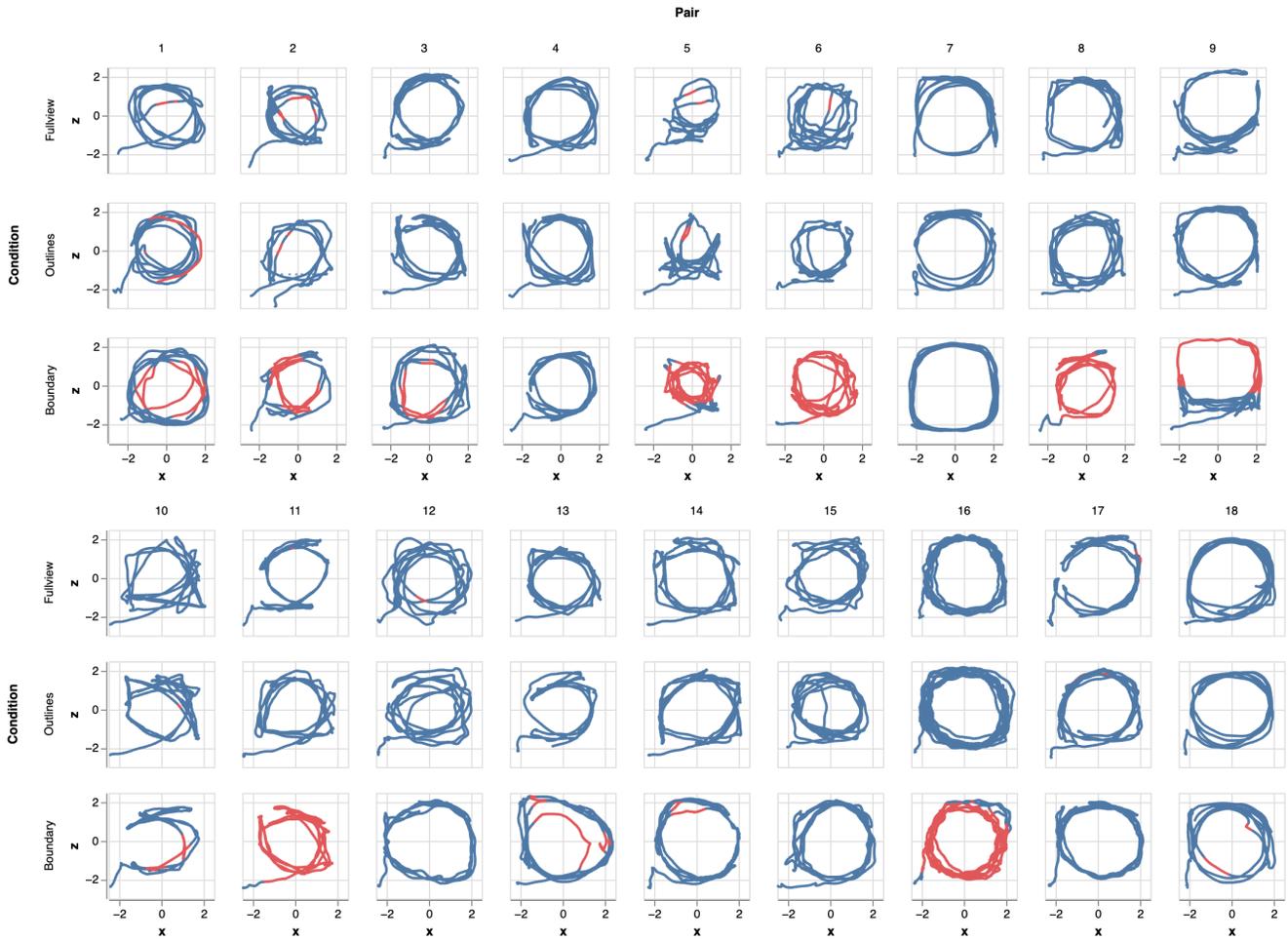
Fig. 9: The motion path of the Walker's head by condition from a top-down view. Collisions shown in red.

the trade-offs between persistent vs. temporary guardian designs, as has been done with VR guardians (e.g. work by O'Hagan et al. [37,43]).

Finally, our findings motivate the need for intelligent context-sensing workspace guardians that assess and adapt to varying awareness needs. In the study, strangers had lower spatial and temporal invasion rates compared to the other relationships, although the number of participants in each group is not enough for rigorous statistical analysis. This is consistent with prior work on proxemics [17], and may suggest that even though the guardians visualize workspace boundaries, personal space may also play a role in avoidance. One participant commented on this, saying *"If I did not know the other person I may have wanted more space"*.

Among participants who had a previous relationship, there were preferences for the Full View Guardian followed by Content Outlines and then the Boundary Guardian. More work is needed to understand whether *who* is in a space may be just as important as *what* and *where* in defining personal workspace boundaries. Prior work on VR guardians has similarly found that the relationship to the VR user is more influential then the setting for considering the notification strategy for bystanders [40]. This may necessitate the need for more socially-aware workspace guardians that adapt the amount of information they share depending on the social context and familiarity of those present. Similar visual adaptions have been made in AR before for representing social networks [35]. These would require more advanced sensing capabilities to understand the social signals and behaviors of users in the moment. If AR workspace guardians can better support social awareness we can avoid proliferating a future where we are together physically but still have the sense of being alone.

6 CONCLUSION

With the increasing prevalence of AR systems in shared workplaces and public spaces, the need for people to establish and maintain their physical and digital territories poses a social challenge to their interaction with other co-located users. We have exposed the lack of research in this area, and present the design and evaluation of three personal workspace guardian techniques for communicating workspace boundaries. The results favor defining guardian systems automatically based on the user's virtual content rather than self-definition. Designers should favor a range of privacy protecting designs based on different tasks, while still providing enough awareness of a user's content and interactions to allow other users to feel comfortable navigating around them. In exploring this design space, we have taken the first steps towards the creation of AR personal workspace awareness systems — systems that are fundamental if AR headsets are to be operated in complex and dynamic everyday social environments with multiple independent users.

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