Personal and Ubiquitous Computing
https://doi.org/10.1007/s00779-019-01306-0

ORIGINAL ARTICLE

Partitioning open-plan workspaces via augmented reality

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Received: 6 January 2019 / Accepted: 27 August 2019

Abstract
Open-plan workspaces are becoming common because of their compact footprint, economic advantages, and capacity for fostering communication. However, users of open-plan workspaces often report a high level of distraction, undermining their performance especially on individual cognitive tasks. Existing common solutions require recurrent physical changes, which are neither practical for companies and employees nor desired by interior architects. In this paper, we examine the use of augmented reality (AR) midair pervasive displays and visual separators to address the problem of visual distractions in open-plan workspaces. While past applications of AR in workspaces mostly focused on content creation and manipulation, we use AR to superimpose visual barriers—what we refer to as *virtual partitions*. To evaluate the impact of virtual partitioning on the occupants' cognitive performance, we conducted two user studies with a total of 48 participants. The design of assessed virtual partitions was informed by interviews that we conducted with 11 professional space designers. The analysis of collected data suggests that virtual partitions can reduce visual distractions and enable users to personalize the visual attributes of their space leading to an improved experience of shared workspaces.

Keywords Human–building interaction (HBI) · Spatial transformation · Augmented reality (AR) · Midair pervasive displays · Virtual partition · Open-plan workspaces

1 Introduction

In recent years, the theme of spatial transformations has been the subject of numerous architectural discourses in the field of human–building interaction (HBI) [2, 3], with HCI researchers contributing to this vision with examples of adaptive architecture [45] and robotic buildings [7]. However, these examples maintain the physicality and materiality of traditional architectural spaces. Considering the current advancements in virtual reality (VR) and augmented reality (AR) technologies [5, 34, 36], we question how digital augmentation of the physical world could be used to alter the perception of the surrounding space or to support the personalization of mixed-reality spaces.

Open-plan workspaces offer the opportunity to test how AR could be used to improve the personal working environment, without impacting the actual physical space. Specifically, the

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00779-019-01306-0) contains supplementary material, which is available to authorized users.

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Published online: 02 October 2019

open-plan layout in offices is currently widespread [9] not only because of its economic viability (it has a smaller footprint than traditional cubicles) but also for its claimed benefit of increasing peer communication [4] and team productivity [41]. However, workers in open-plan spaces often report decreased performance due to distractions [23, 27, 50] and privacy concerns [25]. In this paper, we investigate an opportunity to understand how midair AR surfaces could be used both as virtual pervasive displays and barriers that can decrease distractions from the surrounding space, while retaining the advantages of open-plan workspaces.

Past work demonstrated that it is possible to use surrounding physical surfaces, such as walls, to project or mount screens [49, 55] to create pervasive and interactive displays. More recent studies [28, 40, 47, 51] have explored materials and tools for displaying content in midair. In the context of workspaces, there are similar attempts to design the office of the future [42] with wearable AR or VR devices [5, 18, 19, 52] that allow workers to visualize information on virtual displays. However, these studies are mainly focused on supporting new ways to create and consume content on pervasive displays, rather than focusing on how the users' perception of the surrounding spaces and their attention can be altered by these virtual surfaces. Specifically, we are interested in understanding how virtual surfaces (pervasive displays or visual barriers) can be used to alter the user's perception of space in order to support attention-demanding tasks.

In this paper, we specifically aim to address visual distractions, as past research has demonstrated that irrelevant visual information is one of the key factors that can negatively impact cognitive performance [39]. We present the concept of *virtual partitions* that subdivide an open-plan workspace, using AR superimposed upon the physical world. Users perceive a virtual partition as a physical layer that blocks visual distractions in the surrounding space. To test the feasibility of this concept, we implemented a prototype of a virtual partition and tested its ability to support users' activities compared to not using any partition or using traditional physical separators (e.g., cubicles). Based on the results of the first study, we interviewed 11 space designers and architects to understand what are the real techniques and concerns considered by professional interior designers when creating partitioned workspaces. Taking into account what we learned from the interviews, we revised the visual design of our virtual partitions and tested alternative designs in the second user study, comparing users' performance and preferences.

What we present in this paper is a set of perception studies designed to evaluate the feasibility of AR in altering inhabitants' perception of indoor environments. This paper offers the following novel contributions: (a) we explore the feasibility of employing AR to convey structural spatial elements, such as partitions, that can be used either for displaying more information or to hinder peripheral distractions; (b) we qualitatively investigate the current workspace design methods in partitioning space with professional interior designers and architects; and (c) we quantitatively investigate the performance of "virtual partitions" for shielding visual distractions and evaluated the effectiveness of different physical representations.

2 Related work

This section is divided into three parts. The first part outlines some of the major problems and current solutions in open-plan workspace design. The second part addresses spatial transformation methods using single or multiple media, and the last part summarizes the use of 3D AR technologies for content creation and manipulation.

2.1 Problems of open-plan workspaces: current solutions and limitations

With the proliferation of open-plan workspaces, users and researchers have identified and discussed their shortcomings. For example, Kim and De Dear [25] compared user satisfaction with different types of workspaces and concluded that enclosed private offices substantially outperform open-plan workspaces in most aspects of indoor environmental quality (IEQ), particularly in terms of sound and visual privacy. Shellenbarger [46] specifically highlighted the significance of the problem of visual distraction as the main cause of concentration loss in shared workspaces.

In the domain of space design, the common approach to mitigate distractions has been described as activity-based workplace (ABW). ABW is a widely used workspace layout for offices, consisting of dedicated spaces for specific predefined activities. The idea is that the ability to choose the workspace depending on the current task can amplify users' satisfaction with their work environment [10]. However, more recently, researchers have shown that in practice people tend not to move around the workspace in order to complete different tasks, but rather prefer to stay in a single place [22]. This limitation caused many HCI researchers to think about solutions that do not require bringing users to different workspaces, but rather how to bring different spaces to the users through context-aware adaptation of the physical space. These approaches are addressed further in the next section.

2.2 Activity-dependent space transformations

To support different activities in a single workspace, researchers have investigated how to use structural and material changes in rather experimental ways. Transformations can either require physical changes in structure or more complex dynamics across physical and digital media.

Physical transformations are accomplished in many ways. For example, the Prada Transformer [29] is a 20-m-high tetrahedral rotating structure supported by cranes that can be folded into four basic geometric shapes, each intended for a specific activity (fashion shows, art exhibitions, movie screenings, and special events). Lee et al. [31] created a robotic partition that can actively change shape, implicitly communicating to bystanders what type of activity is currently in place. Specifically, the partition is mounted on three movable robots, which by moving closer or farther away from each other transform its shape. Finally, the Echo-29 wedding hall [6] has a soft inner skin that physically changes its shape according to the spatial layouts needed during a wedding ceremony. The fabric in the hall is also used as a display for image projection.

HCI researchers have predominantly worked at the intersection between physical and virtual shape-changing spaces, specifically in the context of collaborative workspaces. For example, Meagher et al. [37] suggested using ceilings as implicit information displays in open-plan workspaces. Users can therefore be aware of environmental changes in the working environment through subtle visual cues. Zhao et al. [57] used lighting, a beam projector, and sound to create different types of emotional atmospheres in a cubicle, envisioning the future of personalized control of the ambient atmosphere. Kwoka et al. [30], on the other hand, developed a robotic surface that provides physical changes, using a wall-like structure with multiple screens that can change shape to support different needs and activities (e.g., presentations, gaming, privacy, and meetings). Similarly, Grønbæk et al. [21] presented an interactive surface that changes shape between a wall and a table (from vertical to horizontal) to support an informal meeting, with digital content matching the activity projected on the surface. A robotic wall display by Takashima et al. [50] rotates on its vertical axis to allow surrounding users to clearly see the content displayed.

The above-mentioned transforming spaces provide great examples of how space can be modified either physically through the fusion of digital and physical attributes; however, none of these works directly addressed the distraction issue often reported in open-plan workspaces.

2.3 Augmented reality for content creation and manipulation

3D AR is becoming an increasingly popular technology and is currently used in workspaces for both content creation and manipulation. Specifically, with AR technology, users can implement ideas in a configurable immersive workbench using 3D visualization devices, such as smart glasses and head-mounted displays (HMDs). For example, Spacedesign [19] and the work by Usoh et al. [52] are examples of systems that enable designers to sketch, build, and manipulate free-form shapes and surfaces—both individually and in collaboration. ARTHUR [18] is a system that uses an HMD to support complex design and planning decisions for architects. Finally, HoloArt [5] is a system that enables designers to create and paint 3D virtual drawings on real-world objects. Although research into AR technology has demonstrated the feasibility of applying AR in the working environment for immersive content creation, these approaches are still in the early stages of development and lack formal evaluations with users.

Nevertheless, AR technologies are effective tools for content design because they can leverage on the ability to display information beyond the physical boundaries of a computer screen. "The Office of the Future" project is an early example of AR technology applied to workspaces. By displaying information on the space rather than the screen, users can feel immersed in the content and can quickly process the surrounding information [42]. Similarly, Ethereal Planes [15] and the Personal Cockpit [17] suggest ways of displaying information in the air effectively. Lee et al. [32] proposed Projective Windows, a technology for arranging 3D plane windows in an AR workspace, while Ens et al. [16] introduced a layout manager that includes a virtual application window in diverse user environments. Finally, the Remixed Reality [34] project and the work of Malkawi and Srinivasan [36] have shown that users can virtually interact with the real world and that the applications of this technology are not necessarily limited to the workspace. The works in this section clearly show the advantages of the AR technology, which allows users to change surrounding content and environments without changing the actual physical setting. Our work builds on these examples, exemplifying how virtual partitions can be used to support activities in open-plan workspaces.

3 Research purpose and hypotheses

Previous works for transforming space have experimented with diverse approaches for changing space elements' sizes and shapes [6, 21, 29–31, 50]. However, AR technologies, which also could be used to change the surrounding environment [34], have not been fully explored for space transformation in daily usage contexts, such as shared open-plan workspaces. In this paper, we propose to use virtual partitions superimposed upon physical environments so that they can function as effective visual barriers (Fig. 1).

3.1 Prototype

We developed a prototype of virtual partitions based on the Microsoft HoloLens. The choice of Microsoft HoloLens was informed through prior work [54] that studied the feasibility of this device for AR content in three different industries—aviation, medical, and space. The results suggest that there is almost no simulator sickness when using the Microsoft HoloLens. We therefore developed a working prototype of a virtual partition using the HoloLens as an HMD and wrote our software in Unity3D. We designed three-sided partitions that surround a personal work area (e.g., a desk), as shown in Fig. 1. Basically, when a user sits at the table, he or she can see the

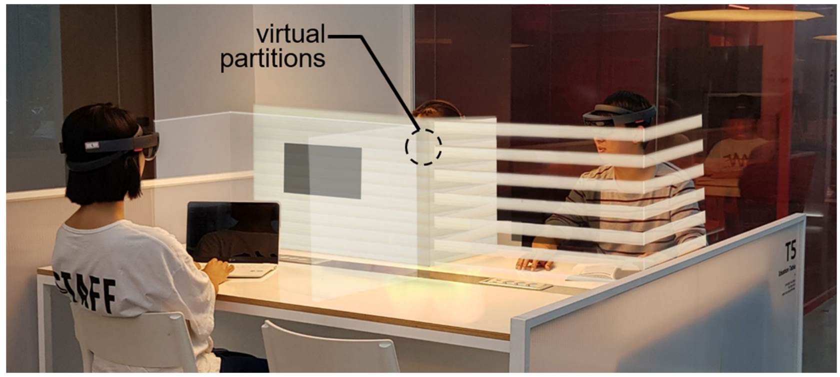

Fig. 1 Example of multiple users using virtual partitions in an open-plan workspace

virtual partitions as if they were real separators. We hypothesize that such partitions can reduce visual distractions from the surrounding space, though clearly, the partitions cannot be used as means of preserving privacy, as they can be seen by people not wearing an HMD.

3.2 Experiment overview and data collection

This paper is composed of two quantitative studies with users and one formative study with expert professional interior designers/architects. In the first study, we investigated how the virtual partition prototype could reduce visual distractions in a shared workspace. The hypothesis that we aimed to validate in this step is the following:

H1 : *Virtual partitions can reduce distraction in a shared workspace.*

Then, we interviewed 11 professional space designers to render insights into common architectural practices and guidelines for designing workspace partitions. The objective of this step was to extract space partitioning design attributes for application to a virtual partition design. Based on the outcomes of the interviews, we prototyped new virtual partitions and conducted another user study to investigate the impact of alternative virtual partition designs and their relationship with the participants' preferences. The hypothesis that we aimed to validate in this step is the following:

H2 : *Preference on the level of openness of a virtual partition is different for each user and correlated with work performance.*

4 Comparing open-plan, physical, and virtual partitions: study overview

We designed a between-subjects study comparing the effects of peripheral distractions on the users' performance when working in the following three different workspace conditions: open-plan layout (OP), physical partitions (PP), and the proposed virtual partitions (VP). Figure 2 illustrates the experimental setup for the three conditions.

We recruited 36 participants (12 female) aged 23–43 (M 28.3, SD 4.85), consisting of 30 researchers, three staff members from our institution, two developers, and one startup CEO. All the participants' habitual workspaces were shared open-plan spaces. Eighty percent of the participants reported that they had been using physical partitions at their workspace, and 81% had experience using AR or VR devices in the past.

All participants were asked to complete a multi-part activity consisting of the following three different exercises: an attention test, a text-editing exercise, and writing a summary after watching a video lecture. The tasks were designed to require continuous attention for approximately 40 min. In order to make fair comparisons across the three conditions, we considered practical tasks that combined the use of a computer and AR for all the three conditions. Users across all conditions wore the HoloLens for the entire duration of the study, viewing some digital content on a physical computer screen while other content was displayed on a virtual screen visible through the AR visor (i.e., on a virtual display). The participants worked on a shared desk (a rectangular table of size 215 × 150 cm), occupying exactly one-third of the table. The rest of the table was used by two experimenters who acted as coworkers and were responsible for creating distracting events in a controlled manner (see Fig. 3). The type, time, location, and duration of the distraction events were the same across all participants and conditions.

4.1 Materials and study procedure

Users sat on their side of the shared table (140 × 75 cm) wearing the HoloLens and facing a keyboard, a mouse, and a computer monitor (Dell UltraSharp, 24 in.). A virtual screen visible through the HoloLens was located on the left side of the physical screen and was used for playing videos while the rest of the content was displayed on the physical screen. Except for the two monitors, in the open-plan condition, no visual obstruction was placed across the table. In both the physical and virtual partition conditions, three solid panels were placed at the edge of the personal workspace with the front facing panel

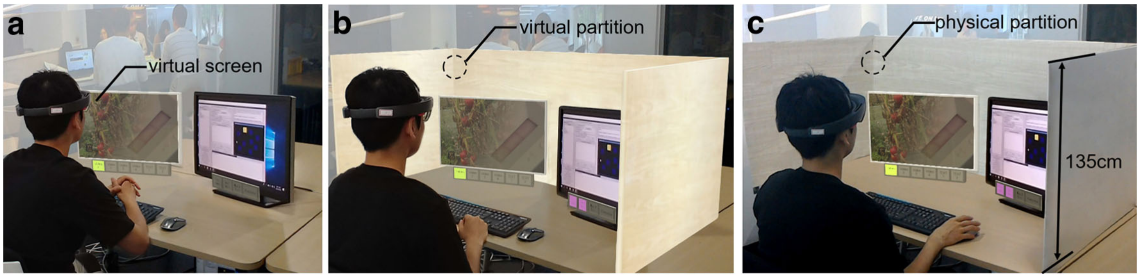

Fig. 2 (**a**) Open plan, (**b**) virtual partition, (**c**) physical partition

positioned behind the monitors (Fig. 2). The panels had the height of 135 cm, corresponding to average height for commercialized physical partitions [35]. The physical and virtual partitions were completely opaque and tinted with a wood pattern. The virtual partition material was implemented using a standard Unity shader, with white albedo color (0x6F6F6FB8), 0.93 emission brightness, and opaque rendering mode.

Each participant completed three tasks (i.e., conditions) in a balanced order. The tasks were based on previous studies that attempted to measure the influence of distractions on work performance [1, 33, 35]. The first task was Corsi block-tapping [12, 48], which is widely administered in cognitive research studies in order to measure short-term visuo-spatial working memory. Corsi was chosen based on the recommendation of Liebl et al. [33] for the measurement of attention in visually distracting situations. The Corsi test was administered through the PEBL software tool [38] on the physical monitor and required input from the mouse.

Following the examples in prior works [1, 35], the second task consisted of watching four short educational videos (extracts from documentaries, lectures, and news; 1 min 45 s each) and writing one paragraph (about three sentences) summary for each video using MS Word. Videos were displayed on the virtual screen while the text editor was displayed on the physical screen. Finally, the last task was a document-editing task performed using MS Word on the physical monitor. Four short film reviews (89–116 words) were combined into a single-text document and edited to contain intentional typos and punctuation errors. The participants were instructed to make appropriate changes to the document as accurately as possible and to save the modified document.

The experiment was organized in the following way. After completing an informed consent form and demographics questionnaire, the users were briefed about the study (10 min). They also completed a preliminary cognitive failure test (CFT) questionnaire [8], which provides a standardized metric for average attention level. The three above-mentioned tasks were then presented in a fully balanced order. Table 1 shows the summary of the tasks. Once a task was completed, the user had to click a virtual button on the HoloLens clicker in order to move on to the next task. Performing all tasks in sequence took approximately 40 min. Finally, the experiment was followed by a post-hoc questionnaire and an interview for 10 min. The experiment took about an hour in total for each participant, and participants were compensated with 10 USD.

4.2 Ecological validity and physical setup

The main challenge in designing this experiment was collecting data that could accurately reflect the experience of users in a real workspace. We considered running the study "in the wild" (e.g., [11]), but, after a preliminary empirical

Fig. 3 Experimental setup: (**a**) projected video scene, (**b**) door-side scene (right side) in plan view. Red dots indicate the locations of virtual partitions. Blue lines show the main acting area

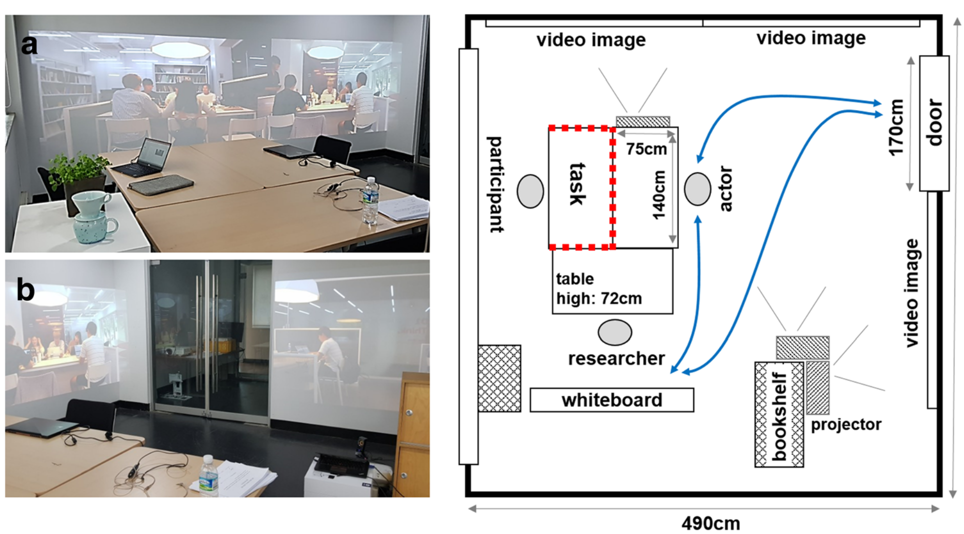

Table 1 Summary of tasks

Task	Time (approximate)	Detail
1) Visio-spatial short-term memory	10 min	Corsi block-tapping task
2) Video summary	20 min	Writing summary of four short media clips
3) Text-editing	10 min	Correcting four short film reviews, which contain intentional typos and punctuation errors

test, we excluded this option because we were unable to control the level of distractions and the time when the events occurred. We therefore opted for a controlled study, in which we could guarantee the number and type of distractions surrounding the users. However, to maintain the ecological validity of the data we collected, we created a realistic environment resembling a workspace, to which we applied different levels of controlled distractions using background video projections and live acting in the foreground.

Specifically, we designed the space considering three layers of distraction, from peripheral to nearby, inspired by the work on public displays by Vogel and Balakrishnan [53]. We constructed a cave (room size 4.7 × 4.9 m) with videos of a real working environment projected on the background walls and had human actors playing roles in the space around the participant's seat. Three videos, each showing 5–6 people working and speaking in an open-plan workspace, were projected on two white walls of the room, in front and to the left of the participant. Background videos, each occupying a surface of 255 × 140 cm (see Fig. 3) were projected on the walls with two ultra-short-throw projectors (EB-585wi, EB595wi) and one LCD projector (EB-G5950). The projectors were positioned to make contents clearly visible and properly scaled to the rest of the environment and give the illusion of being in a crowded workspace. The audio from the videos was reproduced with speakers at 55 dB, which is the typical sound level of a rather crowded workspace [13]. Large furniture, such as a whiteboard and drawers, were placed on the right side of the participants.

Following the example of [14], live actors were used to introduce an additional level of distractions, closer to the users. The live acting consisted of 18 unique actions, such as walking (e.g., passing by or approaching), talking/whispering, using props, dropping small and large objects, gesturing, and looking around. We strove to achieve a balance of actions, having actors interact with both large objects (door, bookshelf, whiteboard, chair, etc.) and small props (cellphone, laptop, etc.). All acting was performed by two researchers who followed a precisely timed schedule, with a total of 18 acting events at intervals of 2 min, for a total of 36 min. If the users could not complete the task by the end of the acting schedule, the actors performed a

Table 2 Distractions provided by experimenters

Task	Time-stamp (min)	Type of action	Details
Corsi block-tapping 5–6 min	0	Walking (passing by)	Passing by the participant.
	2	Walking (approaching)	Approaching to the participant.
	4	Using (desktop)	Sitting and doing work in front of the participant.
	6	Opening (door)	Standing and going out.
Summary 20 min	8	Opening (door)	Coming inside the room.
	10	Walking (passing)	Passing in front of the participant.
	12	Talking (whispering)	Going to the other actor and discussing current events.
	16	Dropping (large)	While sitting, drop a book.
	18	Watching (participant)	Standing at the left-front side of the participant near a wall and watching the participant.
	20	Gesturing (large)	Doing a large gesture to summon another person.
	22	Talking (loud conversation)	Going near to the other actor and asking to fix a plan.
	24	Using (whiteboard)	Draw an image on a whiteboard.
	26	Watching (participant's task)	Standing behind the participant and watching what he/she is doing.
	28	Walking (passing)	Passing in front of the participant.
Text-editing 10 min	30	Dropping (small)	While sitting, dropping a smartphone.
	32	Watching(elsewhere)	Watching places other than the participant.
	36	Gesturing (small–calling)	Calling another person with a small gesture.
	38	Using (bookshelves)	Going to a bookshelf, opening the door, and closing it.
	40	Walking (passing)	Passing in front of the participant.

walk at regular intervals of 2 min for the rest of the experiment. Details about the acting schedule and distracting events are indicated in Table 2.

4.3 Data collection

We used the following method to measure the basic levels of concentration, distraction, and task performance. First, we conducted a standard cognitive failure test (CFT) to check the balance of the concentration level among the participants. The questionnaire consisted of 25 questions about the tendency of participants to make minor mistakes. The participants answered each question on a scale from 0 to 4 (never–very often). Second, to measure task performance, the participants were asked to perform the Corsi box-tapping task, video summary task, and text-editing task. During the task performance session, we tracked head movements and changes in focal point location with the HoloLens mounted on the participant's head. We used these metrics as a proxy for the users' level of distraction. The data was logged with timestamps and stored on the HoloLens. To determine what regions were the focus of the user's attention and their gaze, we predefined discrete regions of potential focus within the HoloLens application. Specifically, focus-events are triggered when the users face any of the partitions (front, left, or right), the desk, the physical monitor, the virtual monitor, or anything in the surrounding background (background front, left, or right).

When participants were facing the physical screen and pressed at the same time the HoloLens clicker at the same time, the task number icon lit up and the start time for the task was recorded. Last, we collected responses for questionnaires measuring *surrounding awareness*, *perceptual immersion*, and *perceived level of distraction* after the performance measuring session. The format for the *surrounding awareness* questionnaire was yes/no responses with confidence levels for each answer. When participants had no idea about an action that happened, they were instructed to choose the lowest confidence level. The *perceptual immersion* and *perceived level of distraction* questionnaires were taken from the study of Liebl et al. [33]. All ratings were in a 7-point Likert scale ranging from 1 ("very low") to 7 ("very high"). Scale increments were numerically marked with the two ends of the scale labeled with opposing keywords. The questions addressed participants' perceived attention, perceived level of visual disturbance, visual annoyance, and immersion.

4.4 Results

One-way ANOVA with post-hoc comparisons using the Fisher's LSD test was conducted for each measure. When the assumption of homogeneity of variance between the groups was violated, we conducted a Kruskal–Wallis test instead. There was no significant difference in the cognitive failure test (CFT) score of the participants between each condition (Table 3).

Table 3 Score of cognitive failure test (CFT), $F(2,33) = 0.47$, $p = 0.63$

	Mean	SD
Open condition	36.25	15.60
Virtual partition condition	36.92	11.31
Physical partition condition	32.42	8.83

Distraction Surrounding awareness was significantly higher in participants in the OP condition than for participants in VP and PP conditions, but surrounding awareness did not differ significantly between participants in VP and PP. Regarding the perceived immersion, concentration, visual disturbance, and visual annoyance, there was no significant difference among the three different conditions. Only in the case of visual annoyance, results were significantly higher for participants in OP than for participants in PP (see Fig. 4).

We counted the events, that is, moments when participants looked to the left or right of their space during the task. As seen in Fig. 5, more events happened in the OP condition than in other conditions. Forty-six events happened in the OP condition, 35 in the PP condition, and the rest (11) in the VP condition. The average event number per person was M = 2.22, SD = 3.08. When comparing the number of events for OP, VP, and PP conditions (Table 4 left), there was a no statistically significant difference between the conditions. However, when only extracting events corresponding to live acting performances (OP, 11; VP, 1; PP, 8), between the different conditions, there was a significant difference in the number of distractions reported (see Table 4 right).

Specifically, the moments the participants looked around due to task-/environment-related events were due to the following actions: whispering, dropping a book, doorbell sound, phone ringing, walking with footstep sound, going outside, whispering, and actor watching the participant. When looking closely at when the events occurred, 69% of total events (55) happened within 30 s before or after task transition. Per task, 54% of total events happened during the summary task (Corsi 29%, editing 17%), with the average duration time of the events being 0.47 s. The number of events that were triggered by a specific distraction (e.g., in Table 2) are 20. Of these, 85% of the events occurred during the summary task (Corsi 5%, editing 10%) and had an average duration of 0.30 s.

Performance The average score on the Corsi task was higher in the PP condition than in the other two conditions, while the VP condition showed higher scores in summary and text-editing tasks. Table 5 shows the detailed scores, and Fig. 6 visualizes the results of the work performance. However, when comparing those results per condition, there was no significant difference among experimental conditions on task performance.

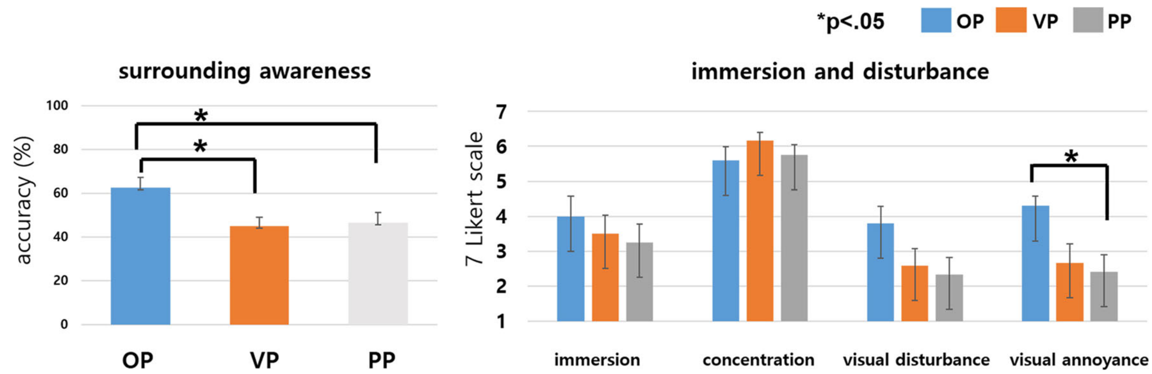

Fig. 4 Surrounding awareness (left) and perceived level of disturbance per condition (right)

Sound influence We collected a total of 92 distractions across conditions, of which only 14 occurred simultaneously with or immediately after an external event. Only 6 out of 14 immediate distractions were caused by non-silent events (e.g., phone ringing, laughing, dropping a book, doorbell). Hence, it was not possible to find statistical differences across partition types for sound. Furthermore, participants in the post-hoc interviews reported feeling distracted and annoyed by the background video and by people walking by across conditions. We conclude from our data that in our settings sound did not play a significant role.

4.5 Discussion

The results support and validate our hypothesis that virtual partitions are as effective as physical partitions in reducing visual distraction. Participants in the open-plan condition were significantly more aware of surrounding actions (average number of events OP = 62.5, PP = 46.7, VP = 45). Regarding perceived disturbance, open-plan participants reported significantly higher visual annoyance than physical partition users, while there was no significant difference between virtual partition and physical partition users (average OP = 4.3, VP = 2.67, PP = 2.42). In addition, open-plan users looked around more often (total OP = 46, VP = 11, PP = 35) than others (see Fig. 5).

A participant from the VP condition mentioned that "the virtual partition was comfortable and helped me to focus on the given task [P2]." Interestingly, participants in physical partition were more distracted than those in the virtual partition condition. The number of distractions from acting events in physical partition condition is higher than that of virtual partition, as seen when plotting the log data over time in Fig. 5. One possible explanation for this behavior could be that the participants in the physical partition felt more secured from outside information, and the reduced perceptual load made it easier for the mind to wander due to internal distractors [20].

However, we were unable to see a clear influence of condition on work performance. Instead, it seems that performance was largely affected by the task type and by the users' natural level of concentration. Specifically, prior work [24] demonstrated that the average block span for the Corsi test of healthy adults is 6.2 blocks (SD = 1.3), but the average score of our participants is 7.8 blocks (SD = 1.3). In other words, the participants of our study, being mostly researchers from a university, have a higher concentration level than the average population, which possibly explains the relatively low level of distractions reported in the studies across conditions. We speculate that if participants' concentration levels were more diverse, the results may have been different. Additionally, the participants reported that they concentrated

Fig. 5 Total number of events across users between task start and end times per space condition

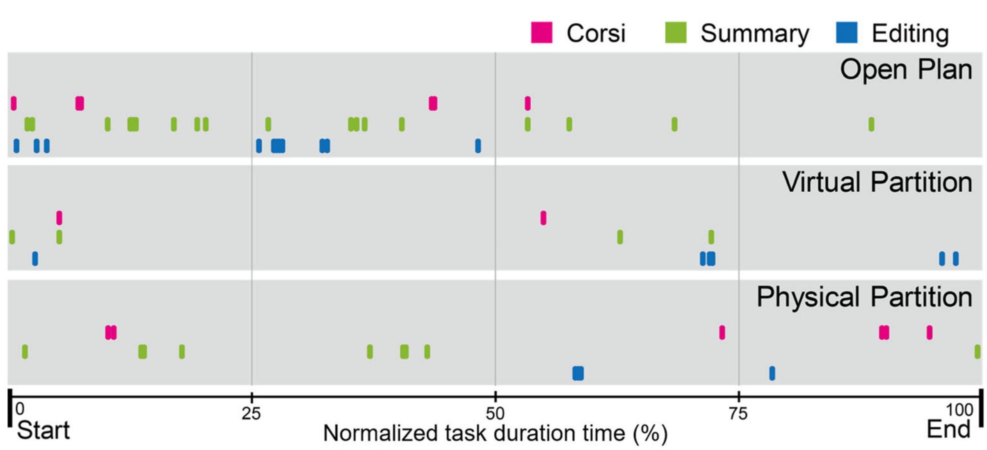

Table 4 Number of events per condition

	Number of events		Number of acted events	
	Mean	SD	Mean	SD
OP	3.83	4.49	0.92	0.79
VP	0.91	0.90	0.08	0.2
PP	1.91	2.11	0.67	1.07
	χ^2 (2) = 3.17, $p = 0.21$		χ^2 (2) = 7.80, $p < 0.05$	

more than usual, as if they were taking an exam, which minimized the difference in performance. P6 (OP condition) said, "I noticed certain noises and would normally have looked, but because I was concentrating on the task, I did not look." Also, the short duration time of the subtasks reduced the influence of outside distractions as the events mostly happened when the participants changed tasks (69%).

Nevertheless, visual analysis of the data shows that Corsi scores were higher in the physical partition condition (average PP = 6.92, VP = 6.58, OP = 6.29), while participants in the virtual partition condition performed better at text editing (average VP = 83.48, PP = 75.14, OP = 74.57). Even though task scores were not significantly different per condition, the average task scores of virtual and physical partition conditions were always higher than those for the open-plan condition.

5 Space partitioning design attributes

In order to determine what physical attributes to consider when designing virtual partitions, we conducted a formative study based on interviews with 11 space designers and architects, aged 30–63 (M = 41.64, SD = 11.32), active across three countries and six cities. Of the recruited designers, five were architects and six were interior designers, all with a minimum of three years of space-design working experience (M = 11.45, SD = 13.77). Six designers were interviewed onsite, and the rest were interviewed remotely through video-conferencing applications. Interviews lasted from 1 to 1.5 h, and each interviewee was compensated with 30 USD.

To understand how the designers actually use spatial elements to partition space, we collected pictures of real designed environments and sketches from designers that describe the spaces they designed. The interview questions were about past design projects in which they had participated and what elements they used in partitioning the spaces. Additionally, we asked about any gaps between the plans and actual usage of the space. All interviews were video-recorded and later analyzed using a thematic analysis.

Table 5 Task scores per condition

	Corsi score		Summary score		Text-edit score	
	Mean	SD	Mean	SD	Mean	SD
OP	6.29	1.62	42.88	9.07	74.57	14.58
VP	6.58	0.87	46.74	5.99	83.48	8.14
PP	6.92	1.10	45.45	9.28	75.14	8.04

5.1 Findings

The workspace designers suggested numerous spatial elements that depend on specific activities and tasks. Furthermore, when they divided a space into multiple subspaces, they reported that they always considered how to build a natural connection between spaces for easy activity switching. Therefore, putting related activity zones as close as possible was an important consideration for designers. Beside functional aspects, what designers were trying to accomplish through their design was "a space with positive variations." They tried to break fixed frames while mainly taking into account pragmatic functions. One designer even said, "A place where de-dailyization [breaking static rules] can be achieved in daily life (D8)." Designers gave liveliness to a static space by changing temperature or color of lighting or by including the outside landscape through the window. Considering the main functions of virtual partitions using AR technology, we organized the collected scripts, pictures, and drawings to classify partitioning elements. Based on the data, we conducted an affinity diagram to categorize them according to design attributes for creating variations of spaces. The following paragraphs describe partitioning elements in detail.

Transparency Controlling transparency is one method of partitioning space. Opaque walls were used to clearly divide a space from the rest of the area. For example, D7 sought to differentiate the atmosphere and improve work efficiency by separating the main workspace from other spaces. On the other hand, a curtain of relatively light material was used to create openness, often with a glass wall (Fig. 7a). "We hung the curtain so that this slightly translucent meeting room could function as a private independent space (D3)". In addition, D9 applied glass materials with partially semi-transparent materials to change the size of a room.

Area covered The other methods consist of using objects to cover the field of view. Designers usually suggest benching (small partition) options for shared desks (Fig. 7c). D6 said that benching has a number of combinations, such as "putting monitors on both sides, removing monitors, hiding the monitor completely, halfway, or opening it completely to control the openness of the field of view." Those options let clients decide the level of openness. In addition, D3 showed how to

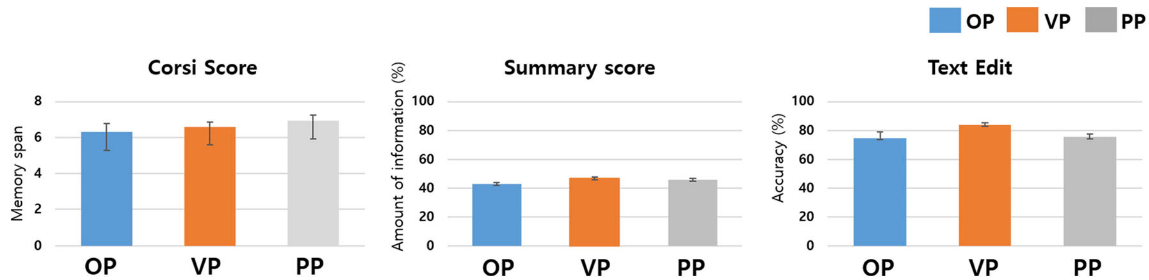

Fig. 6 Result scores of the three tasks per condition

use a bookshelf to divide the CEO's space from the rest of the office (Fig. 7b). Not only whiteboards but also panel-shaped sculptures were used as borders between spaces (Fig. 7d). Moreover, users used their personal objects such as "a flowerpot, a book, a file, or a calendar (D3)" to secure a personal area.

5.2 Discussion and design implementation

During the interviews, we confirmed a conflict of interest between designers/owners and space users. In most cases, the space design was decided by company owners and designers, not individual users. Owners preferred maintaining the determined setup, as they consider it part of their company identity. Furthermore, in the case of large companies, there are space design guidelines, and even small-scale companies have space design rules that cannot be changed by individuals. "We should think about our first intentions. If possible, I want to match all furniture and even props [to the overall design concept] (D4)." However, preferences on space differ according to the individual: "Some person may wish to maintain the place the same, while others want to change their workspace occasionally (D9)." Geographical and cultural differences also play an important role in accepting space design, as mentioned by D6, who pointed out that the design guidelines of a North American company did not work in Asian cultures.

These findings provide an interesting opportunity for the development of virtual partitions. In fact, virtual partitions would not affect the overall esthetic of a space, and it is more likely possible for a single user to customize them and their location in space to suit specific needs. From the interviews, we extracted two basic design attributes for physically partitioning space: transparency and size (area of coverage) of the partition. When designing virtual partitions, these two attributes should also be considered before adding additional features. The partitioning elements from the workspaces of participants are plotted in Fig. 8 along two axes. Figure 8 shows the potential range of virtual partition design, with the horizontal axis being related to transparency and the vertical axis to shape. The top-left quadrant contains opaque materials, while the top-right one contains transparent and translucent materials. The bottom-left quadrant contains various objects,

Fig. 7 Examples of diverse partitioning methods: (**a**) a curtain, (**b**) a bookshelf, (**c**) benching (small partition), (**d**) a whiteboard and a sculpture

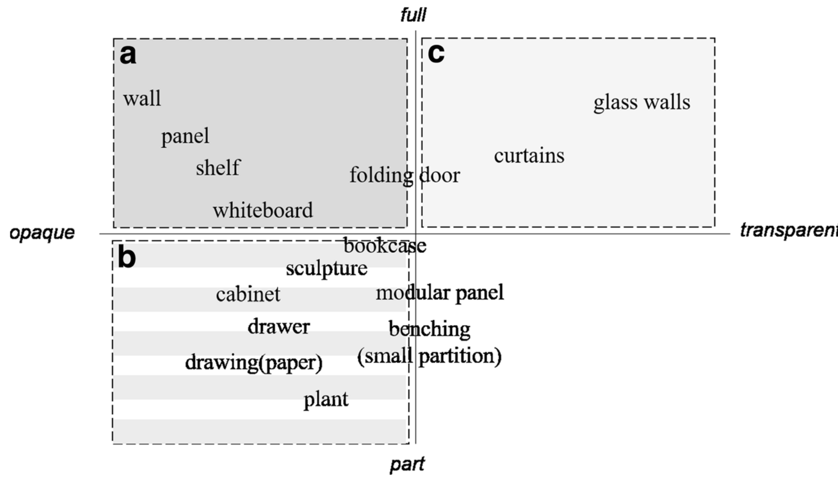

Fig. 8 Partitioning elements from the workspaces of participants control two attributes to divide spaces—area covered and transparency

showing that virtual partitions also have diverse design opportunities taking advantage of AR's flexibility in changing shapes without affecting the physical surrounding space.

6 User preference on virtual partition types

We extracted basic design attributes in partitioning space and, also, revealed that users have different preferences on their given workspace. In this experiment, we applied the design attributes to virtual partitions and investigated the difference in user preference, work performance, and level of distraction per type of virtual partition. For the experiment, we recruited 12 office workers (7 female) aged 23–28 years (M 25.42 years, SD 1.50), consisting of 10 researchers and two local company workers. Eighty-three percent (10 out of 12) of them reported to have been using physical partitions, and 75% (9 out of 12) of them have had experience with AR or VR devices. In addition, they had not taken part in the previous study. We compensated participants with 30 USD for their time.

6.1 Experimental setup and study procedure

We designed a within-subjects study comparing three variations of virtual partitions. Each partition has different levels of openness by controlling the transparency of materials and the range of covered area. These conditions (opaque, striped, and semi-transparent) correspond to quadrants A, B, and C of Fig. 8. The opaque partition is the same as the virtual partition in experiment 1. The semi-transparent condition is also the same, except for using a faded rendering mode. The striped condition divides the basic partition into 12 pieces horizontally (height 5 cm), and half of them are semi-transparent while the other half are opaque. The virtual partition material was implemented using a standard Unity shader with white albedo color (0x6F6F6FB8), 0.93 emission brightness, and opaque rendering mode (see Fig. 9).

In the experimental setup, three participants sat at their desks and used laptops (Dell XPS 13 in., Lenovo IdeaPad U310 15 in., Lenovo ThinkPad T450s 15 in.) while wearing the HoloLens. Figure 9 shows the setup scenes and a plan drawing of the second experiment. During this experiment, the tracking method used was the same as the one in the previous experiment, except that the virtual partition area was divided into 100 smaller areas to increase the accuracy of focal point location tracking.

The experiment's duration was approximately 2 h, with the first 15 min used for introduction and demographic data collection. Afterward, for each partition condition, the participants watched an 18.5-min video with a similar amount of information, summarized the contents, and answered 10 questions about the video. Each condition took about 30 min, and the total time devoted to the task was about 90 min. In the last 15 min, the participants were asked to complete a questionnaire and were asked about 3–5 questions in an informal interview.

In detail, for each condition, we wanted to find the influence of distractions during the task. Because the previous study showed that distracting events happened mostly during moments of task transitions and were not influential to task performance, we decided to use one longer video summary task (1 min and 45 s video from experiment 1). The three conditions were counter-balanced, and while the participants performed the task, an actor acted most of his actions in front of the three participants. A total of 15 actions were planned and divided into five per condition to balance the number of actions for three consecutive conditions. Similar to the previous study, the actions were planned in a timeline to be done in 3 min intervals.

Through the post-questionnaires and interviews, we collected the types and levels of distractions and the timestamps at which they occurred. We, hence, can map the types of distractions to the timeline with the actors' actions and find whether any specific actions were more likely to distract the

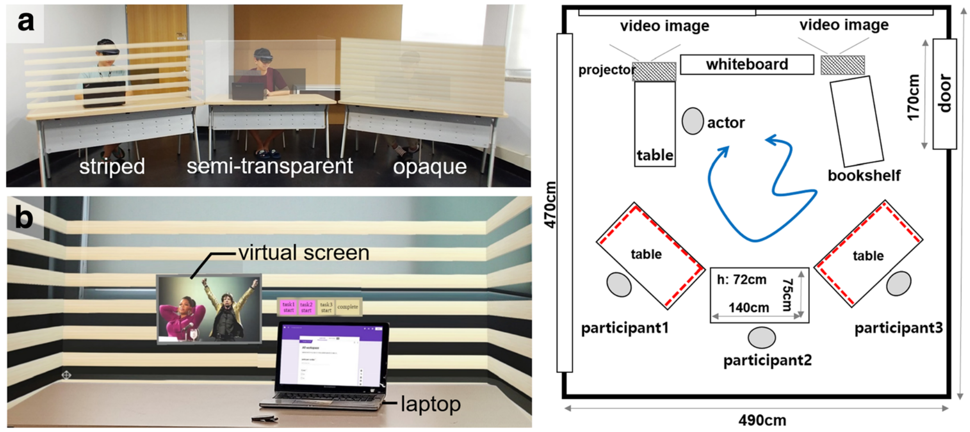

Fig. 9 Experimental setup (**a**) outside view: (from the left) striped, semi-transparent, and opaque conditions; (**b**) inside view of the striped condition; (right side) a plan drawing. Red dots indicate the location of virtual partitions, and blue lines show the main acting area

users. Awareness of the surrounding environment was assessed using a questionnaire with 12 questions, with four questions per condition. We used the verbal measure of approach-avoidance as used in a previous work of Lee et al. [31] (Table 6), as well as measuring direct preferences toward each condition. The approach-avoidance measure asked the participants to rate the experience in space—desire to stay, desire to experience, and desire to affiliate—with both positively and negatively expressed questions. The score of the positive questionnaire and the reversed score of a negative questionnaire were averaged. All measures were answered on a 7-point Likert scale ranging from "strongly disagree" to "strongly agree."

6.2 Results and findings

We conducted a Pearson's correlation test and one-way ANOVA with post-hoc comparisons using the Fisher's LSD test. We found no correlation among preference, performance, or surrounding awareness. In all the three conditions, performance scores were high over 70% (Fig. 10c), and all surrounding awareness scores were below 50% (Fig. 10b). There was no significant difference among conditions on surrounding awareness or the task scores. Figure 11 visualizes average number of times a participant saw a specific area on each partition during the task. There were differences in the actual numbers per condition, but these numbers were not significantly different. Participants in the semi-transparent condition looked around at a wider range of the virtual partition compared to other conditions, especially the striped condition.

There was a strong positive correlation between preference and desire to stay (Pearson's $r(36) = 0.83$, $p < 0.01$, $\eta p^2 = 0.04$). The semi-transparent condition was preferred over the opaque and the striped condition, but there was no difference between opaque and striped conditions (Fig. 10a). The result of the approach-avoidance measures (Fig. 10d,e,f) showed a similar tendency. There was a significant difference between conditions in the desire to stay, the desire to explore, and the desire to affiliate. Additional post-hoc analysis also revealed significantly higher scores in the semi-transparent condition compared to the other two.

The results tell a simple story: regardless of the design type, virtual partitions are effective for reducing outside visual disturbance while the participants perform their tasks. However, because users' preferences are strongly related to their desire to stay in a space, the design of virtual partitions needs to follow individual users' preferences. Therefore, the reasons why participants preferred or disliked a certain partition type should be considered. The participants that preferred the semi-transparent condition explained that it was comfortable for the eyes and gave an "unstuffy feeling." P3 preferred the opaque condition for reducing the amount of outside visual information. He said he lost his concentration while using the semi-transparent condition because he could see the actor walking around. Similarly, P5 and P8 negatively judged the striped condition because the partial outside view between the stripes increased the fatigue of their eyes and caused curiosity toward outside movements. Four of the participants said they unconsciously tried to adjust their head posture to align horizontally with the stripe lines, which caused annoyance.

Table 6 Verbal measures of approach-avoidance [31]

Desire to stay in the situation
(+) How much time would you like to spend in this situation?
(−) How much would you try to leave or get out of this situation?
Desire to explore this situation
(+) Once in this situation, how much would you enjoy exploring?
(−) How much would you try to avoid any looking around or exploring of this situation? (0 = no avoidance)
Desire to affiliate in the situation
(+) To what extent is this a situation in which you would feel friendly and talkative to a stranger who happens to be near you?
(−) Is this a situation in which you might try to avoid other people, avoid having to talk to them? (0 = no avoidance)

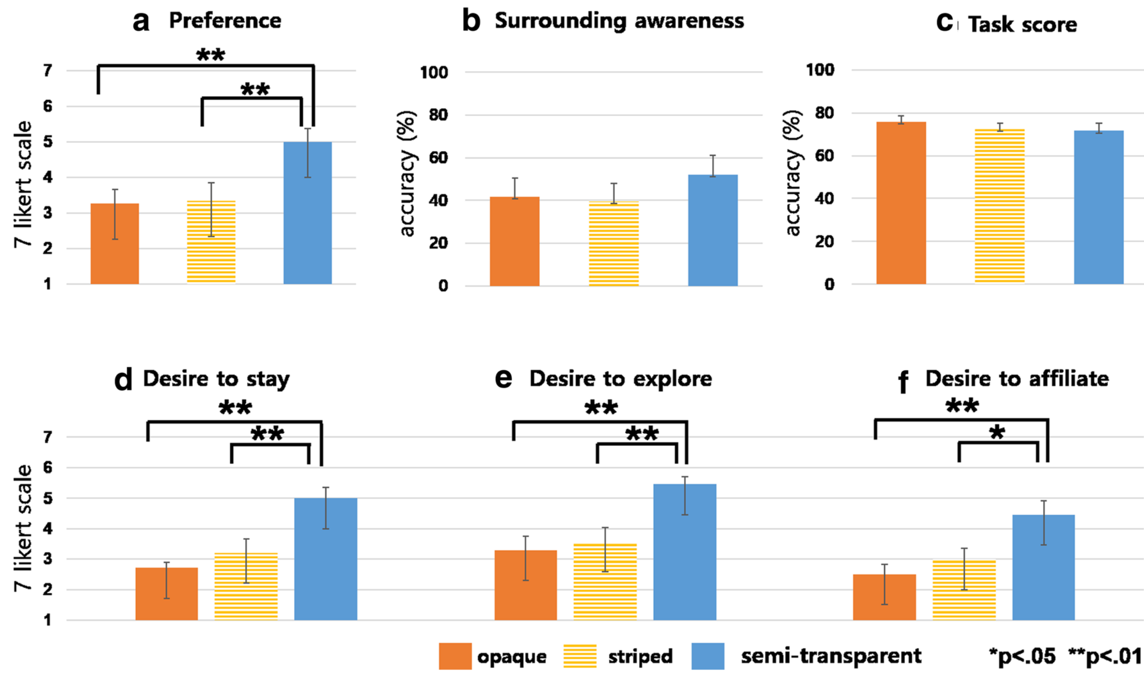

Fig. 10 Experiment 2 results

7 Limitations

This work presents several limitations, mainly rooted in the technical limitations of the HoloLens device. Differently from past work [54], after finishing the tasks, two participants reported light motion sickness, and several people complained about the weight of the device. The limited field of view was the most mentioned issue, resulting in the virtual partition covering a limited area around the screens when the participants performed their tasks. To get a wider view, the participants often leaned backwards, which was reported as being uncomfortable. Furthermore, the HoloLens devices have limited battery capacity, making it difficult to study users' behaviors over long sessions.

Mainly for these reasons, we had to limit the duration of our studies to no longer than 90 min. Although we

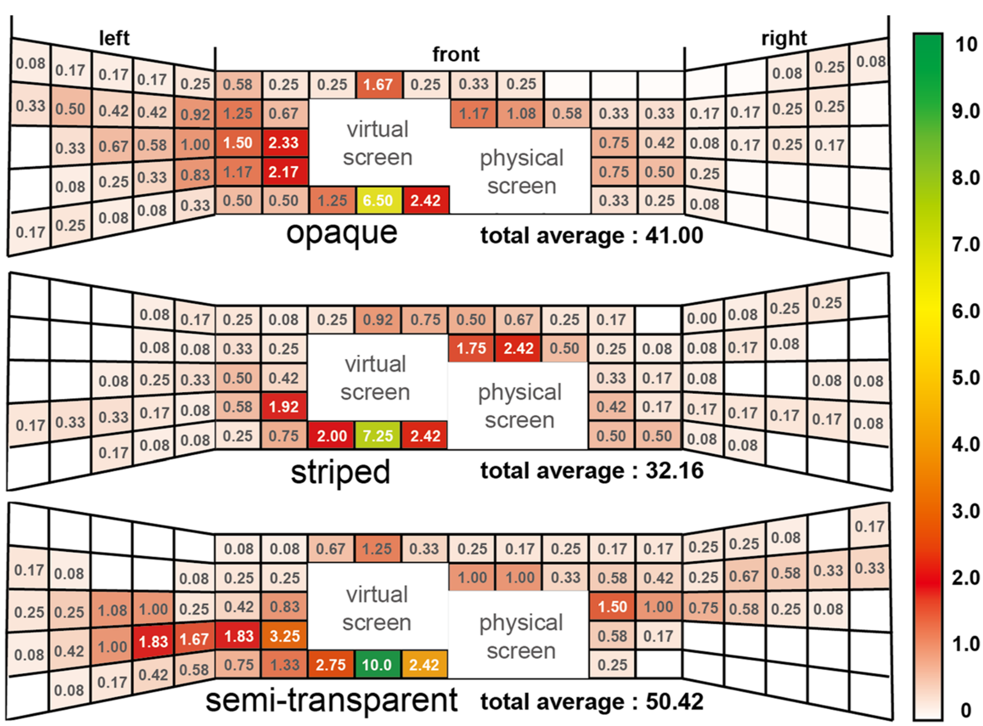

Fig. 11 Visualization of the average number of times the participants looked at the areas of virtual partitions during the task

acknowledge that it would be interesting to test the virtual partition over long sessions and over multiple days, we believe that our findings will be corroborated by longer longitudinal studies. Specifically, we modeled our experiment in light of prior works about the basic rest-activity cycle (BRAC) [26, 43, 44], which describes that the typical span of continuous attention is about 90 min. By having modeled our tasks to last about 90 min, we believe that our results reflect a single cycle for a real-world attention task well. Future works will have to investigate whether virtual partitions can help retain attention across multiple cycles of activities. We also acknowledge that longer observations are needed to achieve higher ecologically valid results, despite our best effort to recreate a realistic working environment in a lab experiment.

8 Discussion and future work

In this work, we introduced the usage of virtual partitions as a space transformation method to mitigate the shortcomings of open-plan workspaces. The first experiment verified that virtual partitions work as effectively as physical partitions in reducing visual distraction. Through the space designer interviews, design attributes for virtual partitions were extracted. We found that the two basic mechanisms for designing a virtual partition are controlling the transparency and the amount of coverage, and these should be considered before trying to add any further functionality to the partitions. We also found that individual users have different preferences in the workspace but are usually not allowed to transform their surrounding space, as it is often pre-determined by designers/owners. The second experiment's results revealed the difference in preferences among users for personalized usage of virtual partitions. All three types of virtual partitions worked equally well in reducing visual disturbances (lower than 50% surrounding awareness) when the participants conducted their tasks. There was a strong positive correlation between preference and the desire to stay ($p < 0.01$). The majority of the participants preferred the semi-transparent partition, but other users preferred the other two variations as well.

The results highlight that virtual partitions can mitigate the shortcomings of the open-plan workspace while not requiring any physical modifications to the workspace. Our study expanded upon the previous study of Zhao et al. [57], who envisioned the future usage of AR technologies as tools to change the atmosphere of the surrounding environment. Specifically, instead of 2D projected augmentation, we used 3D virtual and spatial components and tested our virtual partition prototype in a realistic open-plan workspace setting. As a starting point, we tested a simple partition design. However, more flexible design options can be explored as a next step, because designers in the interviews used diverse design variations in workspace design. As the design of the striped condition influenced the users' acceptance of the condition, we can speculate that explorations of different patterns for shapes, size, and visibility may lead to discoveries about users' increased preference for them while reducing distraction.

While previous AR research focused on creating and manipulating virtual content [5, 18, 19, 52], we highlight that virtual elements can provide independent spatial components around us. Unexpectedly, several participants said that they felt the virtual screen itself was a kind of barrier and did not consider the area behind the screen during the experiments. Even P12 (open condition) said that he sat lower in his seat behind the virtual screen because he was uncomfortable being seen by others. This fact implies that when creating AR content, we should consider external environmental factors along with the surrounding users because any spatial content itself also can influence users' spatial perception. In the context of HBI, this opens a new way of designing adaptive interior spaces in collaboration of space designers and AR content developers. It will bring flexible digital contents to users' surrounding midair surfaces more pervasively.

Lastly, beyond reducing distractions in the workspace, we need to explore other usage contexts related to privacy or sharing. Not limited to personal working activities, diverse usage scenarios in which virtual spatial elements can be applied also include direct and indirect interactions between multiple people. A previous study by Meagher et al. [37] described an environmental display as a subtle indirect communication method. This can be extended to the study of users' behavioral changes by the effect of virtual boundaries. There has already been a study demonstrating that simple spatial elements, such as a string or a carpet, can define the behavior of users and influence users' attitudes toward a task [56]. Prior to all possible future explorations, we believe that our study can serve as a baseline for research about virtual spatial elements that can be integrated into daily life. Therefore, not only space designers but also AR device developers and individual users will be the stakeholders of this perception study about AR space.

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