A User-Oriented Approach to Space-Adaptive Augmentation

The Effects of Spatial Affordance on Narrative Experience in an Augmented Reality Detective Game

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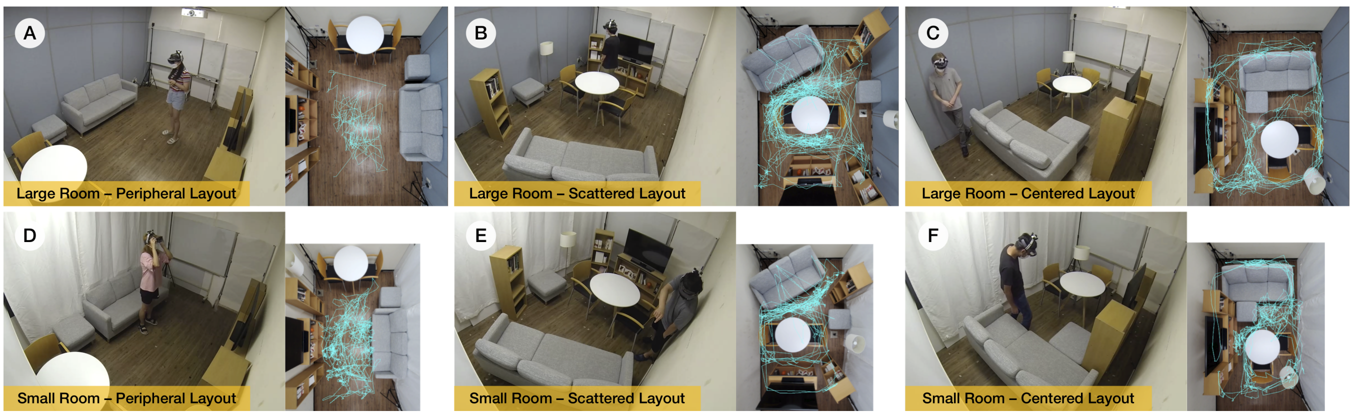

Figure 1: This study explores how traversability and visibility as affordances of real space affect the user experience of Fragments, an Augmented Reality detective game. The images illustrate how the user's range and form of movement differ in each study condition: (A) Large Room - Peripheral Layout; (B) Large Room - Scattered Layout; (C) Large Room - Centered Layout; (D) Small Room - Peripheral Layout; (E) Small Room - Scattered Layout; and (F) Small Room - Centered Layout

ABSTRACT

Space-adaptive algorithms aim to effectively align the virtual with the real to provide immersive user experiences for Augmented Reality(AR) content across various physical spaces. While such measures are reliant on real spatial features, efforts to understand those features from the user's perspective and reflect them in designing adaptive augmented spaces have been lacking. For this, we compared factors of narrative experience in six spatial conditions during the gameplay of Fragments, a space-adaptive AR detective game. Configured by size and furniture layout, each condition afforded disparate degrees of traversability and visibility. Results show that whereas centered furniture clusters are suitable for higher presence in sufficiently large rooms, the same layout leads to lower narrative engagement. Based on our findings, we suggest guidelines that can enhance the effects of space adaptivity by considering how users perceive and navigate augmented space generated from different physical environments.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in HCI**; **Empirical studies in ubiquitous and mobile computing**.

KEYWORDS

Augmented Reality, Head Mounted Displays, space adaptivity, spatial mapping, spatial affordance, narrative experience, storytelling

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1 INTRODUCTION

Augmented Reality (AR) is continuously gaining traction as an innovative medium for interactive narrative experiences rooted in the physical realm [32, 37, 46]. Mounting expectations for its potential are supported by recent developments in AR Head Mounted Displays (HMDs) such as the Microsoft HoloLens2[1] and the propagation of tracking technologies through public software development tools such as ARCore[2] and ARKit[3], which enable easier applications of these technologies in creating AR content for mobile environments [24]. Combined together, these factors present unprecedented possibilities for immersive content beyond the confines of static screens, in which space-adaptive algorithms draw upon geometric information of the real space to create augmented narrative spaces effectively blended into reality.

Despite the growing importance of space adaptivity in designing engaging narrative-driven AR content for HMDs [14, 17, 34], studies on how the real space, the augmented narrative space, and the user within the two coexisting spaces are associated with one another have been scarce [35]. In particular, affordances defined by physical configurations of the real space, which not only determine the adaptive features of the augmented space but also how users conduct themselves during an AR narrative experience, have not been sufficiently analyzed. Most works that discussed the relationship between user experience and the environmental traits of AR or Virtual Reality (VR) [5, 29, 36, 45] did not consider spatial compositions and their affordances from the user's point of view. While Shin et al.[42] have examined how differentiating the size and density of indoor spaces lead to varying levels of user experience during Fragments[4], a space-adaptive detective game played on the HoloLens, they did not apply spatial affordance as the criteria.

To address this gap in research, we expanded Shin et al. [42]'s study to six spatial conditions based on low to high degrees of traversability and visibility as affordances of two types of room sizes and three types of furniture layouts: 1) Large-Peripheral; 2) Large-Scattered; 3) Large-Centered; 4) Small-Peripheral; 5) Small-Scattered; and 6) Small-Centered. In a between-subject study with 72 participants, 12 per condition, we measured presence, narrative engagement, usability, game enjoyment, perceived workload, and task completion time for their experience of Fragments. We also observed and recorded the movement and viewing behavior of participants, combining the logs with semi-structured post-study interviews to identify and analyze commonalities within the conditions in relation to levels of spatial affordances assigned to them.

We found that centered furniture clusters lead to higher presence in sufficiently large rooms, as they afford wide ranges of user movement along predetermined trajectories. On the other hand, the same layout induces lower narrative engagement due to the fact that it causes constant shifts to the users' position and perspective. In addition, usability was higher for participants in the large rooms than those in the small rooms, as the former felt the augmented narrative space was well represented in a spacious environment. Enjoyment and perceived workload were affected by neither room size nor furniture layout. We discuss the implications of these results in regards to patterns uncovered in the users' movement and viewing behavior.

The main contribution of our study is to derive implications on how the space-adaptive design of augmented narrative spaces can be leveraged in altering the spatial affordance of real spaces, thereby improving users' experience of HMD-based AR narratives. Grounded in our analysis, we propose that: 1) controlling user movement through the placement of augmentations; 2) excluding user's blind spots from the augmented narrative space; 3) differentiating space-adaptive strategies according to the content's priority; and 4) considering both the physical and semantic features of the real space are ways that can benefit the user.

[1]https://www.microsoft.com/en-us/hololens/hardware
[2]https://developers.google.com/ar
[3]https://developer.apple.com/kr/augmented-reality/arkit/
[4]http://www.asobostudio.com/games/fragments

2 RELATED WORK

2.1 Space Adaptivity and Narrative Content for HMD-based AR

Space adaptivity for AR is achieved by Simultaneous Localization And Mapping (SLAM), which detects 3D geometric features of the real world and retrieves information such as the composition of surfaces, depths, and lighting conditions while keeping track of the agent's location in real time [22]. This enables reconstructions of the real world that can be used to create and map augmentations presented and placed in accordance to the surrounding physical environment. With SLAM, the augmentations can also be constantly updated to reflect changes in the real world. Over HMDs, this allows for technological innovations to the development and delivery of AR content, as the wearable form factor provides the most seamless interface among currently available mediums for AR [8] despite unresolved limitations in their hardware components such as device weight, display quality, and field of view [12, 33].

Reaching more advanced levels of space adaptivity in an HMD-mediated AR environment is especially crucial for content with narratives, as whether a narrative experience is successful or not depends most chiefly on the degree of engagement it provides to the user [3] through a "perceived realism" of the fictional world it creates [16]. Space adaptivity is the primary means of accomplishing this perceived realism in AR, as the quality of information detected from the real space determines the representation of narrative spaces augmented directly over it. Defined as an area where sequences of events and narrating instances occur [38], narrative space in AR is an entity more literal than figurative, existing as a physical property embodied in the real space. Consequently, past works have theorized on how properties of narrative space and real space jointly create an augmented space [28], stressing the importance of synchronizing the virtual and the real in creating believable environments for AR narratives [39, 41].

In the case of narrative content for AR HMDs, specifically the HoloLens, space adaptivity is realized through a feature termed spatial mapping [13, 47]. Spatial mapping is performed with room scans that process surface volumes and other geometric information detected by depth cameras to form spatial meshes. Cast over the real space, these meshes facilitate realistic placements of narrative elements and plausible interactions between them and the enveloping physical environment: For instance, virtual characters can sit on a real chair or go around a bookshelf when moving from one position to another. Spatial mapping can enable augmented narrative spaces to embellish or transform real space features [2] as settings for stories, virtual tours, and games. Examples of such content include Luna[5], Holotour[6], and Fragments.

Despite the fundamental role space adaptivity plays in devising groundbreaking methods for storytelling through AR HMDs, studies on how this feature can be improved to foster quality narrative content and satisfactory user experiences for them have been insufficient. This owes to the fact that the development and proliferation of AR HMDs are still in their nascency, and that demand for sophisticated narrative experiences over these devices are not significantly high as yet. Specifically, issues on how various aspects of the relationship between the real space and the augmented narrative space affect the user are still largely unidentified.

Past studies that have explored space adaptivity for AR narratives have not ventured further beyond presenting its possibilities, be them in the form of an AR installation [14], a game involving physical objects and environments in an virtual context [17], or narrative content that automatically responds and readjusts to the surrounding real space by using spatial mapping [34]. Their focus was not on investigating the conditions of space-adaptivity for the user. Although Shin et al. [42] found that differences in the size and density of real spaces lead to disparate levels of engagement for the same space-adaptive AR narrative, further studies regarding how such differences can be defined in terms of the ways in which they shape the user's spatial perception and judgments should follow.

2.2 Spatial Affordance and Factors of Narrative Experience in AR Environments

In proposing a framework of affordances for VR and AR, Steffen et al. [43] refer to the concept as relations between the ability of human subjects and features of their environment [9]. They assert that affordance provides a useful lens through which the spatial features of virtually augmented environments and how they affect the user can be examined. Essentially a spatial medium, the defining characteristic of AR is the ability to juxtapose the real and the virtual in physical space [1]. Through this feature, AR affords the user a means to perceive reality in a state where its properties are enhanced, diminished, recreated or created [43].

According to Balakrishnan and Sundar [4], affordance can be translated as perceived action possibilities for user-environment interaction in virtual spaces. In this setting, users' perception of their physical capacities are determined by the mediation of space [49], rather than solely by the space itself. Applying this theory specifically to AR environments, it can be inferred that the coexistence of a virtual augmented space and the real space it derives from work together to afford perceptual abilities that result in decisions on physical movement during an AR experience. As a factor of spatial affordance concerned with movement, traversability is defined as a function of environmental constraints imposed on movement, which also in part determines visibility–another aspect of spatial affordance regarding visual perception [48]–on account of shifts in the user's point of view.

[5]https://www.magicleap.com/experiences/luna
[6]http://www.holoforge.io/work/holotour

A number of previous studies explored how movement and perspective, as afforded by the traversability and visibility of real space, impact various aspects of narrative experience in AR environments. Regarding presence, which is the sense of being within a media experience [11, 27], Tang et al. [45] asserted that the more the users can be aware of their own movements in AR, the higher the sense of presence they can achieve. In addition, Shin et al. [42] argued that the ability to perceive more space-adaptive elements in the AR environment leads to better presence.

In terms of narrative engagement, which is concerned with how immersed the user is in the progression of events during a media experience [7], Nordin et al. [36] stated that more noticeable overlaps of real and virtual elements entail lower degrees of engagement and immersion during an MR game. On the contrary, Shin et al. [42] found that a similar condition created by a large, fully furnished indoor environment resulted in higher narrative engagement. As these studies did not consider the users' movement and perspective in analyzing their findings, we attempt to uncover how differing degrees of traversability and visibility impact this factor.

Regarding usability, the ease of use associated with quality of experience [30], Ko et al. [25] specified the movement of users as one of its key factors in the context of mobile AR applications. Colley et al. [10] stated that the usability of an AR game requiring active user movement was lower when distractions in various forms were perceivable in the surroundings. This is in line with McGill et al. [29]'s study that found usability was lower when there were physical obstacles in the user's vicinity and sudden changes were made to the perceived scene. On the other hand, a contrasting effect was observed when users were afforded sufficient space to perceive the AR environment [19] and move at greater distances [4, 42].

The degree of enjoyment users feel during an interactive narrative experience, particularly in the form of games, is positively associated with presence, engagement, and a moderate level of challenge given [23, 31, 44]. In addition, Shafer et al. [40] stated that providing more interaction in the context of games that involve active movement increases spatial presence and enjoyment. For AR, Hamari et al. [18] also found engagement, enjoyment, and challenge to be evaluated in the same direction for players of Pokémon Go, though the impact of spatial traits to these factors have not been directly considered. Whether these findings can be confirmed for the experience of space-adaptive, narrative-driven AR games for HMDs in various spatial configurations is left to be tested and affirmed through our study.

3 METHODOLOGY

3.1 Research Questions and Hypotheses

For this study, we set the following research questions:

- RQ1. How do traversability and visibility afforded by the size and layout of real space affect presence, narrative engagement, usability, enjoyment, and perceived workload in experiencing space-adaptive, narrative-driven AR content for HMDs?
- RQ2. How do users move and perceive within an adaptive augmented space in relation to the degree of traversability and visibility afforded by the size and layout of real space?

To answer these questions, we drew six hypotheses in accordance with our survey of related work:

Table 1: The configuration of our study conditions set to afford differing degrees of traversability and visibility

<table>
<tr><td colspan="3" rowspan="3"></td><td colspan="6">Spatial parameters of user experience afforded by physical space in AR</td></tr>
<tr><td colspan="3">Traversability[A]</td><td colspan="3">Visibility[B]</td></tr>
<tr><td>Possible Trajectories[A-1]</td><td>Movable Distance[A-2]</td><td>Approachability[A-3]</td><td>Spatial Complexity[B-1]</td><td>Viewable Distance[B-2]</td><td>Perceived Adaptivity[B-3]</td></tr>
<tr><td rowspan="5">Conditions (2 x 3)</td><td rowspan="2">Size</td><td>Large ($15.36m^2$)</td><td>-</td><td>High</td><td>-</td><td>-</td><td>High</td><td>High</td></tr>
<tr><td>Small ($10.14m^2$)</td><td>-</td><td>Low</td><td>-</td><td>-</td><td>Low</td><td>Low</td></tr>
<tr><td rowspan="3">Furniture Layout</td><td>Peripheral</td><td>High</td><td>High</td><td>High</td><td>Low</td><td>High</td><td>Low</td></tr>
<tr><td>Scattered</td><td>Middle</td><td>Middle</td><td>Middle</td><td>High</td><td>Middle</td><td>Middle</td></tr>
<tr><td>Centered</td><td>Low</td><td>Low</td><td>Low</td><td>Middle</td><td>Low</td><td>High</td></tr>
</table>

A. Traversability: An aspect of spatial affordance concerning the movement of the users
A-1. Possible Trajectories: The degree of freedom in choosing the direction and path of movement on the users' own accord within a given space
A-2. Movable Distance: The degree of distance that the users can move at once without being impeded by physical objects within a given space
A-3. Approachability: The degree of ease by which specific areas within the given space can be approached by the user
B. Visibility: An aspect of spatial affordance concerning the visual perception of the users
B-1. Spatial Complexity: The degree of complexity in the composition of physical surfaces within a given space
B-2. Viewable Distance: The degree of distance that the users can visually perceive at once without being impeded by physical objects within a given space
B-3. Perceived Adaptivity: The degree of utilizable surfaces for augmentation, determined by the amount of sufficiently large, enclosed surfaces within a given space

- H1. The sense of presence during a space-adaptive, narrative-driven indoor AR HMD game will be higher in a large room with furniture concentrated in the center of the room.
- H2. Narrative engagement with a space-adaptive, narrative-driven indoor AR HMD game will be higher in a large room with furniture concentrated in the center of the room.
- H3. Usability of a space-adaptive, narrative-driven indoor AR HMD game will be higher in a large room with furniture placed in its periphery.
- H4. Usability of a space-adaptive, narrative-driven indoor AR HMD game will be lower in a small room with furniture scattered across it.
- H5. Enjoyment of a space-adaptive, narrative-driven indoor AH HMD game will be higher in a large room with furniture scattered across it.
- H6. Perceived workload during a space-adaptive, narrative-driven indoor AR HMD game will be higher in a small room with furniture concentrated in the center of the room.

3.2 Study Conditions and Setup

Following the study by Shin et al. [42], we chose stage one of the game Fragments as the testing ground for our hypotheses. Developed for the Microsoft HoloLens, Fragments represents the state-of-the-art in narrative-based indoor AR content for optical see-through AR HMDs. Through spatial mapping, the game detects the spatial features of the room it is played in by requiring the user to perform a room scan, adapts to the room's size and composition of surfaces (ceiling, floor, walls, and raised surfaces), and generates an augmented space closely aligned with the immediate physical environment. The first stage functions as a gameplay tutorial demonstrating the game's space-adaptive characteristics and an introduction to its underlying premise and overarching narrative.

In the game, the player takes on the role of an investigator in the first-person perspective, and is given the mission to track down and capture a kidnapper on the run as the story behind the crime is gradually unraveled. The player-as-protagonist is required to examine various clues augmented in the surrounding real space and piece them together to solve tasks and progress to the next level. The placement of these clues and other game elements are space-adaptive in that they take account of the physical properties of the room acquired through the pre-game room scan procedure.

We designed a 2×3 between-subject study, the six spatial conditions based on a combination of two room sizes (Large, Small) and three types of furniture layouts (Peripheral, Scattered, and Centered). They configured differing levels of traversability and visibility as spatial affordance parameters. For both parameters, we defined three factors–traversability: possible trajectories, movable distance, and approachability; visibility: spatial complexity, viewable distance, and perceived adaptivity–and arranged each condition so that these factors were fixed at relatively different levels (low, middle, high) by size and layout. Details on how the two independent variables were determined are given in Table 1, along with definitions of each affordance and their factors that served as the criteria by which each condition was differentiated.

For a direct comparison with Shin et al. [42]'s study results in terms of how spatial layout, as opposed to spatial density, affects player experience in relation to room size, we applied size conditions identical to their experiment: The Large room condition was set at $4.8 \times 3.2m$ ($15.36m^2$) and the Small at $3.9 \times 2.6m$ ($10.14m^2$), making the area of the Large room 1.5 times bigger than the Small

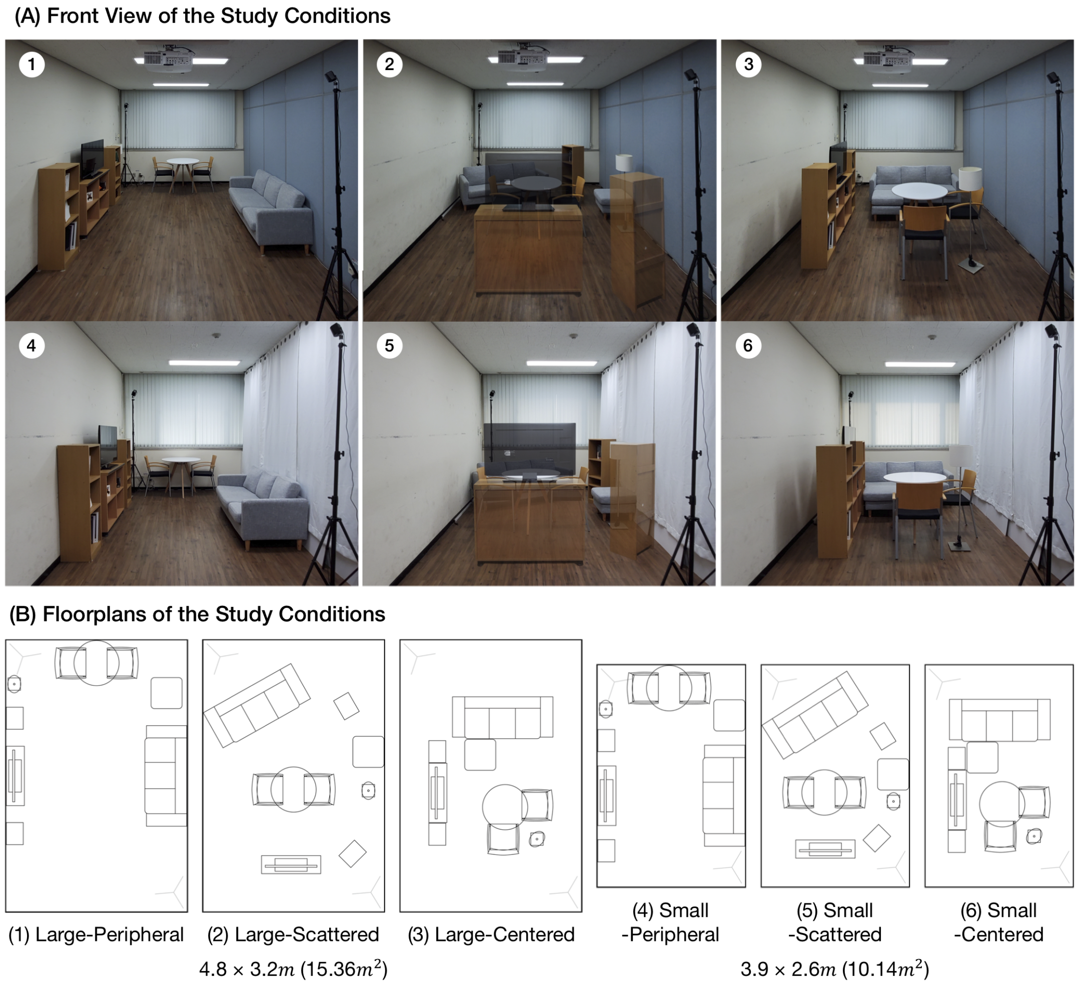

Figure 2: The setup of six study conditions based on room size and furniture layout

one. Both sizes were sufficient for the game to enable successful room scans and map the augmented game space accordingly onto the physical environment, set up in the same office room on campus.

In determining the three furniture layouts, we controlled the number and type of furniture items across all conditions: A total of nine items (A flatscreen TV+TV stand, two bookcases, a dining table, two dining chairs, a three-seater sofa, a sofa stool, and a floor lamp) were selected. For the Peripheral condition, all furniture items were lined up against the walls, leaving most of the floor space in the room empty and unencumbered. In the other two conditions, the furniture was either dispersed throughout the room away from the walls (Scattered) or arranged to form clusters in the center of the room (Centered) to create separate blocks of floor space with differing levels of traversability and visibility.

In order to ensure that each layout represented a plausible and functional living room environment, we applied the interior design guidelines of Merrell et al. [50] and abided by their functional criteria (clearance, circulation, pairwise relationships, and conversation) and visual criteria (balance, alignment, and emphasis) in finalizing the placement and orientation of each furniture item in relation to one another. Figure 2 illustrates the spatial configurations of all six study conditions set up according to size and furniture layout. The floorplans in Figure 2(B) represent exact spatial ratios of the furniture items and the rooms they were placed in.

For all conditions, HTC Vive Base Stations[7] were located at two diagonally opposite corners of the rooms to track and record the participants’ position every second. In addition, a GoPro camera was installed on top of the Station at the inner corner to record the participants’ gaming behavior. External lighting was also controlled to maintain the same level of brightness throughout the study.

We performed a room scan once for each condition before the study sessions and saved the data to the game so that every session for the same condition could be conducted in an augmented game space generated from a single room scan data. Resultly, the spatially adapted layout of the augmented game space and the location of virtual clues (14 in total), which was created anew every time the game was reset for each session, were rendered identical on the whole throughout each condition: In every game space within a

[7] https://www.vive.com/eu/accessory/base-station/

condition, there were only slight variations to the orientation and coordinate values of the augmented objects.

3.3 Dependent Variables

We evaluated six dependent variables–presence, narrative engagement, usability, game enjoyment, perceived workload, and task completion time–as quantitative factors of player experience. First, presence was measured through a modified version of Witmer et al.'s Presence Questionnaire [50]. We eliminated three items on audio fidelity and four on control and display device quality, as all the sound and hardware components of the game were consistent in every condition and unaffected by spatial features. Resultly, a total of 22 items on a 7-point Likert scale for three subscales–involvement, sensory fidelity, and adaptation/immersion–were evaluated.

To examine the degree to which players were immersed in the the game's narrative, Busselle and Bilandzic's Narrative Engagement Scale [7] was employed. Narrative understanding, attentional focus, emotional engagement, and narrative presence were measured through 12 7-point Likert scale items. In this scale, questions on narrative presence were distinguished from the Presence Questionnaire items in that they focused on the feeling of being in a narrative space.

Usability and enjoyment during the gameplay were assessed with the Post Study System Usability Questionnaire (PSSUQ) [26] and the core module of the Game Experience Questionnaire (GEQ) [20], respectively. As with the Presence Questionnaire, four items on interface quality were dropped from the PSSUQ on grounds of irrelevance, leaving 15 7-point Likert items on system usefulness and information quality. Of the core module of GEQ, five out of seven subscales (competence, sensory and imaginative immersion, flow, challenge, positive affect) were measured, excluding two for discomfort (tension and negative affect) through 23 5-point Likert scale items.

In evaluating the participants' perceived workload, the NASA Task Load Index (NASA TLX) [21] was used. The 'raw TLX' [20] approach was applied to obtain self-assessed scores ranging from 0 to 100. Lastly, task completion time was defined by the seconds it took from the beginning of the first stage of Fragments (Memory 1: First Dive), marked with each participant selecting the 'Play in Living Room' button, to the end of the stage, which was signalled by the appearance of an animated icon in the game space.

3.4 Participants

We recruited a total of 72 participants on campus through an online advertisement. Most of the participants were undergraduate and graduate students, all fluent in English to the extent that they had no difficulty in understanding the narrative and following the instructions of Fragments, which could only be played in that language. Their ages ranged from 20 to 40 years (M = 24.86, SD = 3.49). 46 of them (63.9%) identified as male and 26 (36.1%) as female. 12 participants were randomly assigned to one of six conditions.

At the end of each study session, we administered an online Continuous Concentration test developed and distributed for research uses by TestMyBrain.org [15][8] to the participants. It assessed their abilities for analogical reasoning, concentration, and memory, which are essential skills to play a spatial detective game in AR. The purpose of this test was to warrant that the results of the study would not be affected by disparities among the participants' cognitive capacities. As there were no statistically significant differences in the test scores across all six groups ($\chi^2(5) = 4.697$, $p = .454$), the data of all 72 participants were collected and used for our study.

A majority of the participants were new to experiencing narrative-based AR content through HMDs: 34 of them (47.2%) had no prior experience of AR in any form, and 46 (63.9%) participants had never worn an AR HMD before. Considering also the number of participants who replied that they had experienced AR a single time only (16, 22.2%) or tried on an AR HMD just once (11, 15.3%), most of them were wholly unaccustomed to perceiving and navigating AR spaces adapted to the physical environment; only one participant had experienced AR and AR HMDs more than 10 times.

3.5 Study Procedures

The content and procedures of this study were approved by an Institutional Review Board. After the information was explained to the participants in detail, they signed consent forms regarding the study process and the collection of personal and experimental data at the beginning of their sessions. They were then given a briefing on the premise, narrative, and goal of Fragments. This was accompanied by online presentation slides with thorough instructions on how to play the first stage of the game.

Next, the participants were guided to a room set up according to one of six conditions they were assigned to. A researcher was present in the room to assist participants in putting the HoloLens on and practicing the gesture and voice inputs. To start the game, all participants were required to stand at a predesignated spot in the middle of the room while facing the same direction. Once they selected the play button, they were left on their own in the room for the gameplay. They were told to move freely around the space without any time limit on finishing the stage.

After the study task, participants filled out a series of questionnaires in the following order: 1) a personal information questionnaire containing items on age, education level, occupation, prior experience of AR and AR HMDs, gaming habits, and familiarity to spatial mystery games; 2) the Presence Questionnaire; 3) Narrative Engagement Scale; 4) PSSUQ; 5) GEQ; and 6) NASA TLX. Upon completing them, they were subject to a semi-structured interview focused on how the spatial features of the room they were in impacted their game experience. As the final step, participants took the 15-minute-long Continuous Concentration test. The duration of every study session was approximately one hour.

4 STUDY RESULTS

To analyze subjective measures gathered through the questionnaires, we used the Aligned Rank Transform (ART) proposed by Wobbrock et al. [51] for non-parametric analysis ($\alpha = 0.05$) in handling the two independent variables (room size (*size*) and furniture layout (*layout*)), along with interactions between them. All pairwise comparisons for the post-hoc analysis were Bonferroni corrected. Internal consistency among test items was examined based on the

[8]https://www.testmybrain.org/

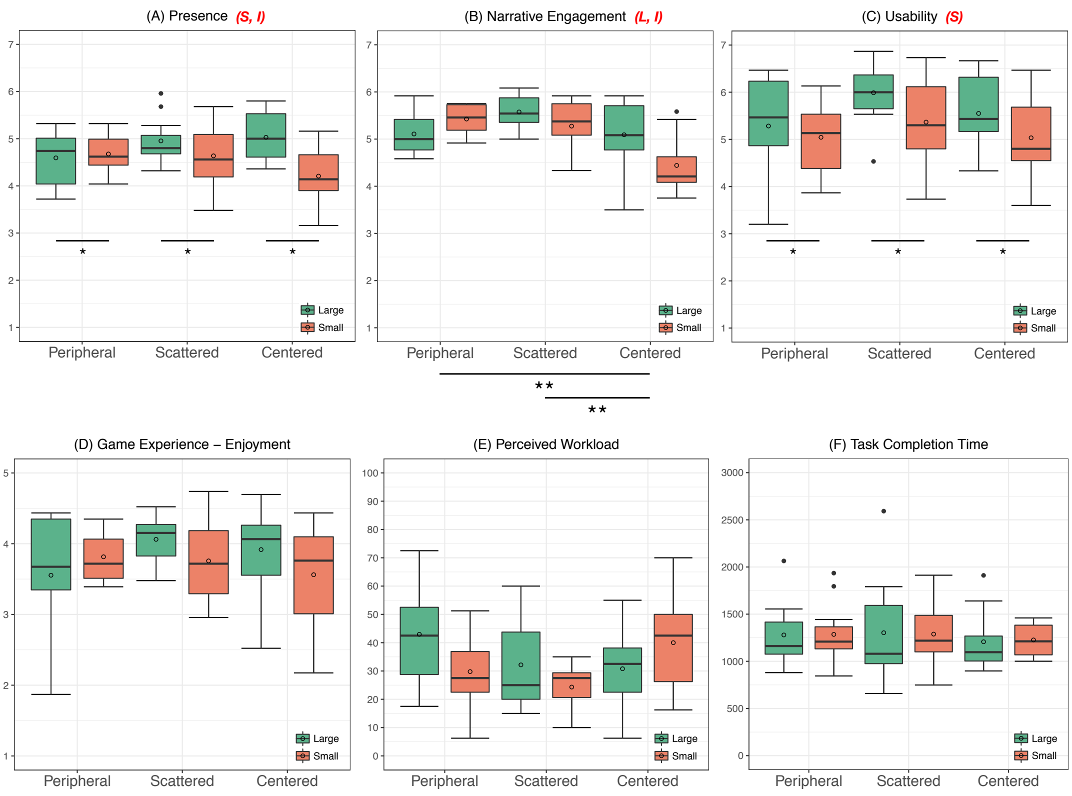

Figure 3: (A) Presence rating results (PQ); (B) Narrative Engagement rating results (Narrative Engagement Scale); (C) Usability rating results (PSSUQ); (D) Game Enjoyment rating results (GEQ-Enjoyment); (E) Perceived Workload rating results (NASA TLX) and (F) Task completion time (in seconds) (S and L: significant effect of Size and Layout, respectively; I: significant Interaction effect between the two independent variables)

reliability coefficient of Cronbach's alpha. For the objective measure of task completion time, the normality of data distribution was tested through the Shapiro-Wilk test. Because the distribution was not normal ($W_{LC} = .825$, $p = .020$), we applied ART for non-parametric analysis ($\alpha = 0.05$) among multiple factors. For both the subjective and objective data analysis, we excluded outliers such as extreme values, errors caused by the data recording device, and invalid inputs attributed to participant misinterpretation.

The core statistical results presented in Figure 3 are summarized as follows:

1. Players in the Large room with furniture clustered in the center felt a higher sense of presence than those with furniture lined against the wall during the game.
2. Narrative engagement with the game was lower when the furniture items were in the center of the room than when they were lined against the wall or scattered across the room.
3. The usability of the game was higher in the Large rooms than in the Small rooms.
4. There was no significant difference in the enjoyment players felt during the game across all conditions.
5. Neither room size nor furniture layout had a significant effect on the player's workload for the game.
6. Both room size and furniture layout did not have any significant effect on task completion time.

4.1 Presence

The internal consistency of the participants' PQ scores showed an accepted level of Cronbach's alpha ($\alpha = 0.820$). The size of the rooms had a significant main effect on the PQ scores ($F(1, 55) = 6.535$, $p = .013$) but not furniture layout ($F(2, 55) = .577$, $p = .565$): Participants who played in the Large rooms experienced higher presence than those who did in the Small rooms, except for those in the Peripheral layouts. Furthermore, a significant interaction effect between room size and furniture layout was found ($F(2, 55) = 3.580$, $p = .035$): In the Large rooms, presence was higher for the participants who played in the Centered layout compared with the Peripheral. However, presence was higher for those in the Peripheral layout than the Centered in the Small rooms ($p = .023$).

4.2 Narrative Engagement

Results on internal consistency indicated an accepted value of reliability ($\alpha = 0.747$). A significant main effect was found for furniture layout ($F(2, 45) = 7.165$, $p = .002$) but not for room size ($F(1, 45) = 2.705$, $p = .107$). The post-hoc analysis showed significant differences between the Peripheral and Centered ($p = .044$) layouts and

Figure 4: Visualizations of every participant's movement for each study condition, represented as (A) normalized heatmaps to depict range and (B) accumulations of their trajectories to depict form

the Scattered and Centered ($p = .002$) layouts: Participants in the Centered layout felt less engrossed in the game story than those in the Peripheral and Scattered. Furthermore, a significant interaction effect with room size for the Peripheral and Centered layouts ($F(2, 45) = 4.934$, $p = .012$) were found. Whereas narrative engagement was higher for those in the Small room than in the Large room for the Peripheral layout, it was higher in the Large than the Small for the Centered layout.

4.3 Usability

For the PSSUQ scores, an internal consistency among the measured Likert items was found ($\alpha = 0.906$). While there was a significant main effect for room size, usability being higher in the Large rooms than in the Small rooms, ($F(1, 55) = 6.304$, $p = .015$), layout of furniture did not have any ($F(2, 55) = 2.422$, $p = .098$). In addition, there was no significant interaction effect between the two factors ($F(2, 55) = .102$, $p = .903$).

4.4 Game Enjoyment

For enjoyment, the collected answers satisfied the accepted level of internal consistency ($\alpha = 0.920$). Both room size and furniture layout did not have any significant main effect on the participant's feeling of enjoyment during the gaming experience (*size*: $F(1, 55) = 1.668$, $p = .202$; *layout*: $F(2, 55) = .646$, $p = .528$). There was also no significant interaction effect between the two factors ($F(2, 55) = 1.226$, $p = .301$).

4.5 Perceived Workload

Both room size and furniture layout did not have a significant main effect on the NASA TLX scores (*size*: $F(1, 50) = .580$, $p = .450$; *layout*: $F(2, 50) = 2.160$, $p = .126$). Moreover, there was no significant interaction effect between the two factors ($F(2, 50) = 2.214$, $p = .120$): The participants' perceived workload was not significantly different among the six conditions.

4.6 Task Completion Time

No significant main effect was found for task completion time in terms of both room size and furniture layout (*size*: $F(1, 50) = .457$, $p = .502$; *layout*: $F(2, 50) = .224$, $p = .800$). A significant interaction effect was also not found between the two factors ($F(2, 50) = .075$, $p = .928$): The relationship between room size and task completion time was independent of layout, and that between furniture layout and task completion time was not affected by room size.

4.7 Participant Behavior and Comments

During the study sessions, we tracked, recorded, and observed the participants' behavior to uncover notable traits that can provide insight to the quantitative results. These traits were associated with patterns in the participant's movement and viewing behavior that differed according to the spatial affordance of each study condition. The findings were further corroborated by participant interviews.

4.7.1 Movement. In order to analyze data collected through the Vive Trackers, we chose two visualization methods. First, we generated normalized heatmaps from an accumulation of timestamps that recorded the participants' position in the room every second. This was to identify the participants' range of movement in each condition, as depicted in Figure 4(A). Second, the trajectory of each

(A) The space behind the sofa in the Large-Scattered Condition (B) The space behind the TV in the Large-Centered Condition

Figure 5: The locations of common blind spots found in the (A) Large-Scattered and (B) Large-Centered conditions

participant was visualized by connecting the timestamps in chronological order. By compiling all trajectories within every condition, as presented in Figure 4(B), we aimed to observe commonalities in the participants' form of movement afforded by each space.

The heatmaps show that in the Large rooms, the participants' range of movement increases in the following order: Peripheral, Scattered, and Centered. Whereas most participants in the Large-Peripheral condition chose to stay in the middle of the room, close to their starting position, those in the Scattered and Centered conditions of the same room size traversed wider ranges, the latter more so than the former. On the other hand, there was no marked difference among the range of movement for participants in the three Small rooms.

The trajectories reveal that for both size conditions, the Centered layout induced a more restricted form of movement for the participants than the Scattered and Peripheral layouts. The degrees of freedom in the participants' trajectories were largely determined by configurations of the floor surface: When the furniture items divided the room into discernible subspaces, they afforded predefined paths that the participants inevitably had to stay on during their gameplay (P2-6: "*I didn't really want to go around the furniture when I was playing because it was inconvenient, but I had to.*"). As the clusters of furniture items in the Centered layout led to the most structured and separate units of subspace, most participants traversed the rooms in a uniform trajectory that encircled those clusters.

In addition, both the heatmaps and the trajectories indicate that across all conditions, participants generally avoided moving towards the outermost, non-functional areas of the rooms they were in, regardless of whether there was sufficient space in those areas for them to do so. This tendency was more apparent in the Scattered and Centered layouts for both size conditions, where the spaces behind the back of the sofa and TV set were approached much less (P3-10: "*It was strange that there was space between the wall and the furniture*"). Despite the fact that the augmented game elements were placed in those areas as well, the participants' priority was to navigate the inner area of the room enclosed both spatially and functionally by the furniture that faced inwards.

4.7.2 Viewing Behavior. In order to analyze how participants perceived the augmented game space in each condition and conducted their gameplay accordingly, we recorded videos of the sessions seen from the participants' viewpoint with the camera on the HoloLens they were wearing and captured their activities with a GoPro camera installed in the rooms. Playbacks of the videos revealed three major traits in their viewing behavior.

First, participants perceived a greater disparity between the real space and the augmented game space when the information presented in the room was more visually complex. A majority of participants who played in the Centered condition commented that despite the game's apparent space adaptivity, the two spaces seemed to be separated rather than merged together by it (P3-1: "*The virtual space and physical space felt mismatched.*"; P3-2:"*I could clearly tell the difference between what was real and not.*"). This was reflected in how they treated both the physical and virtual aspects of the game as impediments to their mission when they collided with one another and complicated their sight (P3-7: "*It bothered me when the clues clashed with the background*"): When the furniture partly occluded the augmented clues, participants tended to first move away from the scene to search for other clues that appeared against a simpler background and examine them instead.

In contrast, many participants in the Peripheral layout–more in the Small room–expressed positive feelings on how well the the augmented game space seemed to be adapted to the real space (P1-2, 4-2: "*I could understand the game better because it matched the real space.*"; P4-3: "*I felt that clues augmented around the sofa went well with the scene.*"). Being able to perceive most of the room's surfaces at once, they found it easier to comprehend the association between the two spaces in their entirety and locate clues provided via the adaptive overlaps (P1-1: "*The space was pleasant to play the game in, with no disturbances*"). As they found less incongruities in their field of view, they rarely made unexpected readjustments to their viewpoints in search of more visible targets.

Second, blind spots that were not immediately visible to the participants or largely neglected during their visual investigation were found in the Scattered and Centered layouts. Their locations are shown in Figure 5. In these conditions, participants experienced more difficulties in detecting clues augmented on the outer rim of the rooms, their boundaries determined by how the furniture items confined the room's practical functions as a living room within the middle area (P5-2: "*It was hard to find clues behind the shelves or the sofa*"). As all participants began the game in the center, furniture items placed near the walls blocked their views of the floor and part of the walls behind them. Coupled with the fact that many of them chose not to venture beyond the boundaries, these spaces were chiefly isolated from the participant's gameplay.

Additionally, participants in the Scattered and Centered layouts also had a harder time perceiving clues on the floor near their feet, especially in the Small rooms (P5-10: "*I couldn't find clues on the floor at first because of the sofa and the bookshelves*"). As units of empty floor space divided by the two layouts were significantly more limited in size, the game space augmented over them left even less empty space available for the participants to utilize. In line with observations made by Shin et al. [42], the participants treated virtual human characters in the game as if they were physical entities and tried to avoid moving or looking through the space occupied by them. This restricted their visual search routes to the narrow strips of floor surface they allowed themselves to traverse along, the levels of their gaze dropping to lesser degrees as they moved more cautiously than participants in the Large rooms.

Third, participants on the whole were inclined to establish a connection between the practical, real-life functions of the furniture in the physical space to their roles in the fictional, augmented game space in relation to the virtual game elements (P6-12: "*I wished the furniture in the room could reflect the theme of the game more*"). For example, a number of participants attempted to interact with the TV screen or focus their gaze on it, despite the fact that no interaction cues or augmented clues were given in its vicinity. They stated that this was on account of the fact that they expected the TV to serve its actual purpose within the game as well (P5-10: "*I wondered why nothing showed up on the real TV during the game*"). Some others tended to direct their attention to the bookshelves or the open storage space of the TV stand after detecting the existence of clues such as a printed timetable or a ticket, assuming that it would be more likely for additional clues such as those to be found near them.

5 DISCUSSION

5.1 Analysis on the Study Results

Our statistical results showed that the level of presence during Fragments was significantly higher in the Large-Centered condition. We therefore accept H1, which stated that a large space with furniture items clustered at the center will elevate the sense of being in the game. Among the six conditions, this setting induced the widest range of movement in the most restricted form: Both of these patterns were afforded by furniture clusters that divide a sufficiently large space into distinct, easily traversable subspaces where single path options in between led to a uniform gameplay trajectory.

Although the degree of traversability was highest in the Peripheral layout and lowest in the Centered, the participants' actual movements were to the contrary. While those in the former condition were provided with the largest area of unobstructed floor space to freely move about in, this served as the very reason they chose to not to: They could perceive all parts of the room well enough to conduct their gameplay without having to approach a certain location. On the other hand, those in the latter condition had to play against challenges caused by the complex composition of walls, floors, and raised surfaces to search for clues. This led to them to move more actively along the limited paths configured by the furniture clusters, evading the occlusion of clues and mismatches between the real and virtual space they observed.

Following previous studies asserting that more exposure to one's own activities results in higher presence [45], we consider this to be the primary reason for the positive association between the level of presence and the range of movement. Regarding how a prescribed form of movement afforded through multiple furniture clusters contributes to the same factor, we infer that being able to perceive one's expected course of movement and act accordingly, as opposed to wandering without direction, anchored the participants more firmly to the spatial aspect of being in the experience. Based on comments that moving around the furniture clusters made them aware of the adaptive AR space they were in, we assume that this heightened their feeling of physical involvement in the game. This is in line with a prior report that asserted more visual representations of the connection between the real and virtual space contributes to increased levels of presence [6].

Next, narrative engagement was significantly lower in the Centered condition compared to the Peripheral or Scattered, with an interaction effect concerning room size between the Centered and Peripheral conditions. This leads us to reject H2, which posited that narrative engagement would be higher in the Large-Centered condition. This finding contradicts Shin et al.'s study, which found that presence and narrative engagement were both significantly higher in large spaces on account of the similarities the two factors share in the context of experiencing space-adaptive AR narratives. At the same time, it aligns with Nordin et al.'s [36] in that increasing the visibility of the real space through a complex composition of raised surfaces and floor space led to lower engagement.

We postulate that a tradeoff between presence and narrative engagement occurred in the Centered condition because the degree of movement and perceived adaptivity afforded by the layout affected these factors in opposing ways. Whereas moving actively in a wider area and perceiving the augmented space in detail from the Centered was beneficial for presence, such physical activities caused constant shifts in the participants' position, viewpoint, and the augmented information within their sight. Together with the fact that common blind spots obscuring the clues were created by the layout, this seems to have had a negative impact on the participant's ability to connect the clues dispersed in space and concoct a cohesive narrative, leading to lower levels of engagement. That many participants in this layout made note of conspicuous gaps between the real and the augmented space further supports our claim, as they stated they felt distracted from the events when they became aware of them. Adding to this, the connection participants mentally established between the function of furniture items–more noticeable in the middle of the room–to their role in the augmented game space seems to have reinforced this gap when their expectations were not met.

Usability was rated significantly higher in the Large rooms compared to the Small ones, with no interaction effect regarding furniture layout. Consequently, we partially accept H3 and H4 that posited usability will be higher in the Large-Peripheral condition and lower in the Small-Scattered condition. Counter to our assumption that the Peripheral would affect usability positively and the Scattered negatively through their spatial affordances, the layout of furniture did not impact the participants' judgment on the quality of their game experience. Instead, the size of the rooms as configurations that determined the degree of movable and viewable distance were found to be associated with this factor: Participants felt that the augmented game space and its interface were better represented and more interactive when they could perceive and move about in a large space. This aligns with previous work that found securing sufficient space for the user to control virtual objects is crucial for the usability of AR applications [19, 29].

Turning to game enjoyment, perceived workload, and task completion time, neither room size nor furniture layout had a significant effect on any of these factors. We thus reject H5, which expected the degree of enjoyment will be higher in the Large-Scattered condition, along with that which posited self evaluations on physical and mental effort during the game will be higher in the Small-Centered condition (H6). We attribute these results mainly to two aspects of our study: 1) the characteristics of Fragments and 2) the participants' overall lack of experience regarding space-adaptive AR content over HMDs.

Fragments requires players to search the augmented game space freely to deepen their understanding of the game's story and solve problems based on the clues placed in it. Moreover, it does not impose any restrictions on playtime for a given stage or mission. Therefore, task completion time depended primarily on each participant's play style rather than the spatial conditions they were in: While some prioritized the experience itself, focused on being in the augmented space and exploring its components in detail, others were more goal-oriented and prioritized the challenge given to them, aiming to complete the stage as fast as they could. We believe that this resulted in the non-association of the study conditions to task completion time and also to workload, as the amount of physical and mental effort put in by the players are to an extent determined by the duration of their play and the degree of concentration maintained in the game.

Furthermore, that most participants had hardly any experience in playing AR games while wearing HMDs was found to have affected their impression of Fragments. Across all conditions, many participants commonly remarked that the novelty of interacting with augmented objects placed adaptively in the real space, together with the compelling, well-executed narrative structure of the game, made the experience intriguing and enjoyable overall. As the measure for game enjoyment included participants' evaluation of the positive aspects of the game, this may have offset differences in the level of immersion or challenges induced by the spatial affordances in each condition, which were also assessed for this factor.

5.2 Design Implications for a User-Oriented Space Adaptivity

Based on our analysis, we propose three main design implications on the space-adaptive composition of augmented narrative space and one supplementary implication regarding the detection of real space. These suggestions aim to enhance the effect of narrative-driven AR content for HMDs in various configurations of indoor spaces from the user's perspective.

1) Control user movement in real space through the adaptive placement of augmented objects: Our study shows that the range and form of movement afforded by the size and layout of real space affect various aspects of user experience within the augmented game space adapted to it. Additionally, it reaffirmed observations from a previous study that players involved both physically and mentally in an AR narrative experience tend to behave as if virtual objects and human characters possess real, tangible properties. Therefore, we suggest that these elements should be utilized to complement the makeup of real spaces that afford movement less beneficial to the user's narrative experience in a space-adaptive AR environment. For example, augmenting clusters of furniture items in the center of the real space when it is detected to have a large, empty floor surface will raise the level of presence by affording a wider range of movement along a more predictable trajectory for the users. In case the target real space is not big enough for the augmented space and its elements to be interacted with more easily, choosing to place virtual objects where the composition of surfaces are complex rather than simple will secure more space for the user to move around in and make the room appear as large as possible, thereby contributing to higher presence and usability.

2) Exclude users' blind spots in the real space from the adaptive augmented space: Another way to construct space-adaptive AR spaces that better support the users is to define, detect, and detract sections of real space that are less visually and physically accessible to them. When the layout of a room creates multiple blockages that obstruct the users' field of view and movement, it leads to areas that are commonly disregarded, rendering the information augmented on them as largely missing from the AR experience. As this has a negative impact on the user's ability to establish a mental blueprint of an AR content's overarching narrative as the sum of its parts and engross themselves further in it, we recommend that these areas be removed altogether in overlapping the augmented space. Our findings indicate that when a small room with furniture scattered across the room is scanned, avoiding 1) narrow floors between the furniture and the walls; 2) non-functioning spaces beyond the back of the furniture; and 3) eye-level surfaces occluded by the height of objects near the periphery in placing augmentations may increase the relatively lower level of narrative engagement induced by the space.

3) Align space-adaptive strategies with the main goal of the AR content: Our study found that a trade-off between presence and narrative engagement exists in certain spatial layouts. Consequently, manipulating this configuration into a specific setting through modifications on space-adaptivity, as was put forth as our first and second design implications, may inevitably emphasize one aspect of the AR experience at the expense of the other: While setting up a large, complex environment divided into clear subspaces is suited to obtain higher presence, it is negative in terms of narrative engagement. In such cases, determining which of the two factors is more essential to the AR content's intended purpose and applying space-adaptive rules accordingly will be crucial to the design process: When providing an experience unique to AR as a medium is deemed important, narrative being the means, the space adaptivity of the content should first contribute to optimal configurations for presence. On the other hand, when the focus is on delivering the narrative of the content, AR being the means, space-adaptive measures should be utilized in ways more favorable for narrative engagement. As an example, designers can either choose to utilize subunits of floor space for higher presence or block out blind spots and complex areas for higher narrative engagement through space-adaptive augmentations in a large physical space.

4) Consider not only the physical but also the semantic features of the real space : Our study implies that a more effective merging of the real and the virtual within a space-adaptive augmented space can be achieved by utilizing the functions of the real space and its physical components in the design and placement of virtual content. As the real environment houses the augmented space and its elements, the two spaces presented in parallel, users expected real objects to serve their original roles in the AR environment as part of the content. Therefore, interpreting the physical space as a semantic entity can provide a more convincing narrative setting to the experience, as opposed to treating it as a mere spatial backdrop composed of geometric planes and depth information. This can further contribute to bridging the gap between the real and the virtual that users perceive in rooms with complex spatial layouts. Strategies such as mapping a virtual screen over the real TV or placing augmented food on a dining table, provided that these elements are relevant to the content's narrative, may increase presence, narrative engagement, and enjoyment for the user.

5.3 Limitations

The limitations of our study are mainly concerned with the structure of Fragments, the study conditions, and participant characteristics. First, that Fragments is a single-player game where the story progresses largely through interaction with inanimate objects invites the possibility that users may perceive and evaluate their experience differently when the augmented narrative space is structured in contrasting ways. The spatial mapping method used in Fragments, common to all space-adaptive content for AR HMDs, determines the visible layout of augmented space and the ensuing space-user dynamic in principal. However, particularities regarding its narrative content and format, while based on basic elements of interactive storytelling shared in the genre, may have affected the outcome of our study in ways that are irrelevant to the affordance of different spatial configurations.

Second, decisions on the specific size and layout of our study conditions could have been more objective and thorough to gain more accurate insight on the relationship between spatial affordance and user experience for space-adaptive AR narratives. Notwithstanding the fact that size conditions identical to a preceding study were observed for direct comparison, setting up a wider range of size conditions between an area too small or too large for the game to scan would have enabled a more in-depth analysis. Regarding layout, principles other than shifting the position of furniture items from the periphery to the center to control degrees of traversability and visibility may have yielded other notable results.

Third, that most of our study participants had little to no prior experience in AR may have counterbalanced the effects of spatial affordance during their gameplay. As most of the participants were expressly occupied with the novelty of the AR device, gaming environment, and space-adaptive content, this could have influenced their assessment of the dependent variables on the whole. Therefore, recruiting participants with varying degrees of AR experience, categorizing them into different groups based on the criteria, and setting up the study so that the ratio between the groups is balanced for each condition would be needed for similar studies in the future.

6 CONCLUSION AND FUTURE WORK

In this work, we examined how the traversability and visibility of six different spatial configurations, determined by size and furniture layout, affect users in their experience of a space-adaptive AR detective game played through the HoloLens. A between-subject user study of 72 participants found that whereas centered furniture clusters creating complex surfaces facilitated a better environment for the sense of presence in a large space, they had a negative impact on narrative engagement. Usability was higher in the large rooms, but no significant differences were found between the conditions for workload, game enjoyment, and task completion time.

We conclude that space adaptivity should consider the ways in which spatial affordance shapes user behavior and perception: Managing user movement and excluding blind spots through flexible applications of space adaptivity in the design of AR narratives will improve user experience and enhance the content's impact. Additionally, adopting segmentation-based tracking to incorporate the semantic features and relationships of real space and objects in the detection process will also advance the effects of space adaptivity, as opposed to relying solely on geometric information.

We plan to expand the scope of our study to other formats of narrative-based AR content in various domains. In the case of multiplayer AR games or remote AR collaboration systems, where the same augmented space is shared by a number of users in different physical environments, it is highly possible that the affordance of each space will impact each user in ways that differ from our current findings. Furthermore, we wish to explore diverse characteristics of both real and virtual objects that configure adaptive augmented spaces and how they affect spatial affordance. Ultimately, we wish to apply our design implications in developing AR narratives with improved space-adaptive features to test and confirm their validity.

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