© 2022 IEEE. This is the author's version of the article that has been published in the proceedings of IEEE International Symposium on Mixed and Augmented Reality (ISMAR). The final version of this record is available at: 10.1109/ISMAR55827.2022.00068

ABOVE & BELOW: Investigating Ceiling and Floor for Augmented Reality Content Placement

Marc Satkowski [*] Rufat Rzayev [†] Eva Goebel [†] Raimund Dachselt [*] [§]

Interactive Media Lab, Technische Universität Dresden, Germany
[§] Centre for Tactile Internet with Human-in-the-Loop (CeTI) and Cluster of Excellence Physics of Life, Dresden, Germany

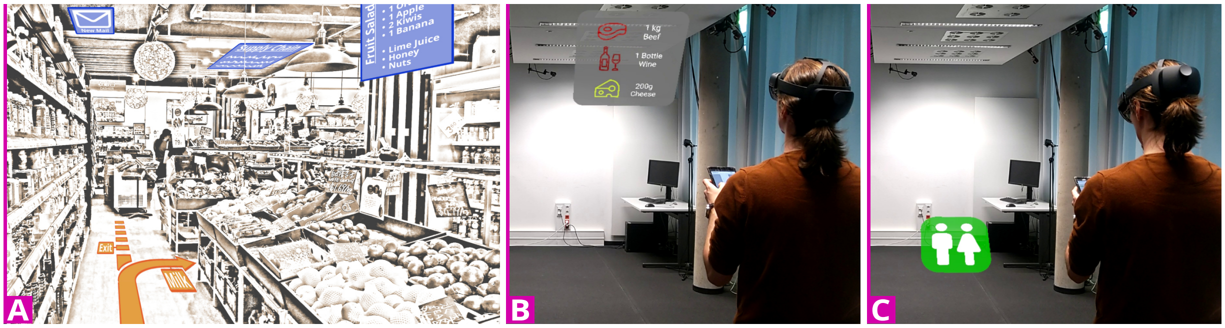

Figure 1: Envisioning a future AR application displaying content on the ceiling and the floor. `(A)` illustrates a small grocery shopping scenario. The arrows on the floor help navigate the supermarket, while the content on the ceiling shows a notification, part of a shopping list connected to a recipe, and supply chain information for a product. `(B)` and `(C)` show scenes from the second study in this paper. A participant controls the content placement using a tablet.

ABSTRACT

Augmented Reality (AR) interfaces support users by providing access to digital content within real-world environments. However, displaying content at the users' eye level might result in the occlusion of the real world. Therefore, it requires finding AR content placement areas that free the users' field of vision. In this work, we systematically investigate two content placement areas beyond the users' eye level: the ceiling and floor. To understand how potential users perceive virtual content on the ceiling and floor and how the content should be placed on these areas, we conducted two user studies. While the first exploratory study showed the general usefulness of either area, the second quantitative study allowed us to define optimal placement parameters regarding visibility and comfort. With insights from our studies, we provide design recommendations for future AR applications that support 2D content presentation on the ceiling and the floor.

Keywords: User Study, Augmented Reality, Mixed Reality, Ceiling, Floor, Content Placement.

Index Terms: Human-centered computing—Mixed/Augmented Reality; Human-centered computing—Visualization

1 INTRODUCTION

Technical advancement and an increasing amount of personal devices enable retrieving and exploring information in many everyday life situations. Enhanced availability of digital information combined with augmented reality (AR) user interfaces opens up new possibilities for displaying and interacting with digital information [2]. As AR enables the simultaneous presence of reality and digital content by embedding virtual information into real-world scenes, it is possible to support primary real-world tasks. For example, digital labels can enrich a shopping experience [9], navigational aids can help to orientate in unknown buildings [43], or in-situ content can be used to find and refer to new information in museums [54]. Fundamentally, displaying information using AR requires well-grounded placement strategies and view management [6]. To avoid the occlusion of essential real-world information in front of the user with AR content, extending the current placement options beyond the eye level becomes necessary.

Therefore, this paper systematically investigates displaying virtual content on the *ceiling* **above** and the *floor* **below** the user as promising placement areas beyond conventional eye level in indoor AR environments. In this paper, we focus on 2D virtual content that can provide valuable information in various everyday life situations. With this, we aim to generate a better understanding of whether and how the ceiling and floor in indoor environments can be used to place 2D virtual content using AR applications.

The ubiquity of both areas, also motivated by other research (e.g., [12, 58]), opens up new possibilities for displaying digital content. As both areas are easily accessible through a simple head or eye movement, content placement on these areas is also interesting for the research direction of glanceable interfaces [37]. For example, the ceiling and the floor in a supermarket (see Fig. 1A) can be used for the presentation of additional information, like displaying information about particular vegetables, showing a grocery list, helping a user navigate through the building, or displaying notifications.

While previous research has used these areas for content placement (e.g., [51, 56]), a more profound and systematic treatment of the design dimensions considering AR content placement is still lacking. To fill this research gap, we comprehensively investigated AR content placement on the ceiling and the floor in indoor environments via two user studies. While with the first study, we focused on a qualitative analysis of how the placement of 2D AR content on the ceiling and the floor is perceived, the second study investigated optimal placement parameters in these areas. Based on our combined qualitative and quantitative data analysis approach, we provide the following contributions: `(1)` A systematic treatment of

---

[*] e-mail: [msatkowski, dachselt]@acm.org
[†] e-mail: [rufat.rzayev, eva.goebel]@tu-dresden.de

2D AR content on the ceiling and floor, including the definition of placement parameters and perceptual issues. **(2)** Two user studies focusing on generating insights on general usability and specific placement strategies for both placement areas. **(3)** Six design recommendations and future research directions for using the ceiling and floor in indoor AR applications based on our findings. We also provide an appendix with additional material and information as well as the study prototype code base on our project page[1].

2 BACKGROUND AND RELATED WORK

Our work is related to previous research on ubiquitous content placement using Augmented Reality (AR) and using the ceiling and floor as the virtual content location that we discuss in the following. A more detailed survey of research related to ceiling and floor (see Sec. 2.3) can be found in Appendix Sec. A respectively.

2.1 Ubiquitous Content Placement in AR

AR interfaces are receiving increasing interest [8,28]. They allow placing and visualizing arbitrary virtual information ubiquitously and are therefore related to the concept of ubiquitous computing (UbiComp) [63]. Fundamentally, UbiComp predicts that computing devices pervade everyday objects [18] and even human beings themselves [4]. AR and UbiComp pursue a similar goal of intertwining computational capabilities and the everyday world. However, AR functions are fundamentally different since those focus on enhancing the users' skills and are not modifying the environment itself [21,34].

As AR systems, especially head-mounted displays (HMDs), enhance the users' visual capabilities, the perception of the shown virtual content is of high relevance [16,31,53], which can be affected by the content placement. In situated data representations, virtual content is placed close to the physical referent [14,64]. Overlaying virtual content directly on top of the real-world object can increase immersion and is known as embedded visualizations [64]. Virtual content can be placed directly in front of the user and within the field of view (FoV) of an AR HMD. However, considering various forms of virtual content, such as simple labels [3,46,52], signage [1,10], manuals [19,29], or information visualization views [32,50], overlaying or embedding them in the environment leads to occlusion of the real-world environment. In addition, the real-world background could also negatively influence the perception of the virtual content and their related tasks [53]. Therefore, a body of work investigated solutions for avoiding occlusion in AR HMDs and balancing virtual and real-world information visibility in the FoV. This includes view management algorithms to reduce the occlusion in the FoV and increase the understandability of the virtual content [46], finding optimal placement strategies for several contents simultaneously [6,33], and the investigation of the visibility of content on optical see-through HMDs [39,55].

In addition, several researchers suggested using glanceable peripheral interfaces on AR HMDs to reduce the information load in the users' FoV [27,30,37]. Therefore, ceiling and floor are two promising areas for virtual content presentation in indoor environments, as they are easily accessible through a well-known and rather close location to the eye level and to a primary task.

2.2 Properties of Floor and Ceiling

Several properties of ceiling and floor make them promising areas in indoor environments for displaying information. The floor, as always available and visible surface [17], can be used not only for decorative or aesthetic purposes [49] but also for guiding persons [65] by changing elevation levels, like separating pedestrian paths by borders, the placement of objects, or additionally placed signs, e.g., boundaries of bus stop areas. The ceiling in indoor environments is almost always visible (e.g., [59]), mostly planar, and remains free and featureless [60] except having light sources or object attachments (e.g., banner, curtains, or fans) [44,65]. Both ceiling and floor provide easy and effortless access, making them suitable for presenting glanceable interfaces [37,41]. However, several constraints, including users' posture [61], available space and variable heights of the ceilings, should be considered while displaying information on the ceiling or floor. Moreover, due to unobtrusiveness, users might miss paying attention to information on a ceiling [26,59], or it can be tiring to look at the ceiling for an extended amount of time [58]. Lastly, the presence of static (e.g., chandelier) or dynamic (e.g., human) objects can also make placement challenging.

2.3 Displaying Virtual Content on Floor and Ceiling

Displaying content on ceiling and floor was already explored in several use cases, such as indoor and outdoor guidance (e.g., [51]), office work (e.g., [65]), smart living spaces (e.g., [26]), or industrial applications [47]. To display content on these areas, monitor systems, stationary and wearable projectors and HMDs were mainly used in previous works. We can group these works into *UbiComp solutions* and *personal augmentation* considering the used display technologies (see Tab. A1 and Sec. B in Appendix).

Within the related work, setups can be found which make use of stationary display technology, such as single or multiple displays systems (e.g., [40]), low-resolution displays consisting of individual LED units [62], or projector setups (e.g., [44]) to display content on these areas. However, due to the stationary and embedded properties of such configurations, the augmentation is limited to a predefined local area and is presented to everybody in the environment, while parts of the augmentation could be occluded by people or objects.

Another smaller group makes use of mobile devices, such as pico-projectors (e.g., [12]) or HMDs [51,56] for content presentation on the ceiling or the floor. For HMDs, it was shown that interfaces which require users to look at the floor for navigation permanently are not optimal with regards to ergonomics [51]. However, it was also found a preference for displaying a map location on the floor in front of users than on their hands or as a floating display [56]. Yet, due to the mobile nature of such devices, it is challenging to optimize the augmentation based on the current environment. While the previously mentioned works supported navigation tasks with floor visualizations, to the best of our knowledge, no previous studies have systematically investigated content placement both on the ceiling and the floor using AR HMDs.

2.4 Summary

In summary, previous work showed that AR has the potential to situate or embed virtual information directly into the real-world environment, whereof the optimal placement of such content is of general interest. The related work shows that ceiling and floor can be used as alternative placement areas for virtual content. However, the literature further showed that only a few papers looked into how AR HMDs can be used to augment either area while also revealing a general difference between them. Therefore, we see a gap in systematically understanding how the ceiling and floor can be used to display AR content, including a particular interest in optimal content placement in these areas.

3 CONTENT PLACEMENT ON CEILING AND FLOOR

For efficient content placement on the *ceiling* and *floor*, it is essential to understand the parameters and the constraints affecting the placement. Therefore, in the following, we describe possible parameters (see Sec. 3.1) and potential perceptual issues related to the content placement on the *ceiling* and *floor*, and introduce the angular size as an important placement measurement (see Sec. 3.2).

---

[1] Project page: `www.imld.de/Above+Below`

© 2022 IEEE. This is the author's version of the article that has been published in the proceedings of IEEE International Symposium on Mixed and Augmented Reality (ISMAR). The final version of this record is available at: 10.1109/ISMAR55827.2022.00068

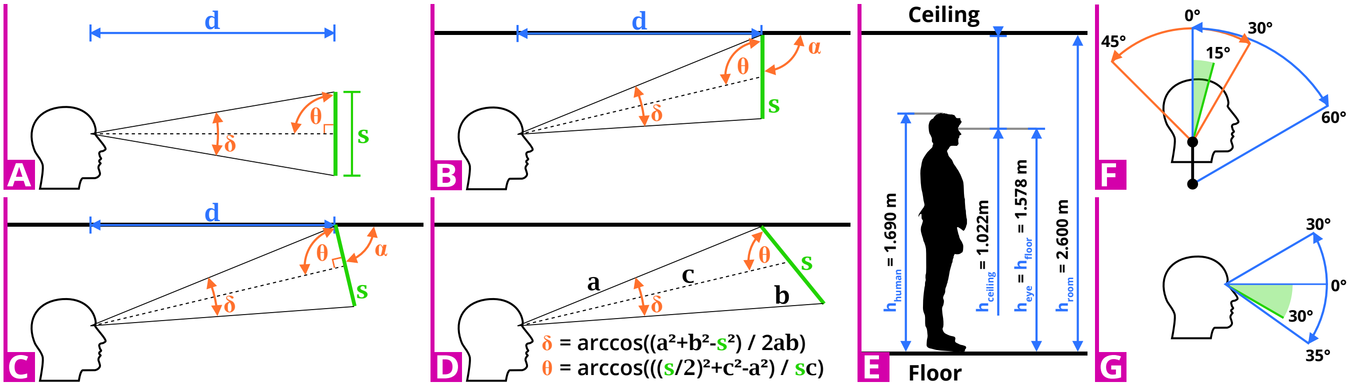

Figure 2: Calculation of the angular size (δ) and viewing angle (θ) **(A-D)**, and information about the human ergonomics and the measurements of typical environments **(E-G)**. **(A)** The angular size (δ) can be calculated by distance (d) and size (s) of the object, while the viewing angle (θ) is orthogonal to the content. **(B)** As the content is placed on the *ceiling* (or *floor*), the viewing angle (θ) is no longer orthogonal. **(C)** The pitch (α) can be changed to achieve an orthogonal viewing angle (θ). **(D)** To calculate the angular size (δ) and the viewing angle (θ), the distances from the eyes can be used. For content on the *floor*, as a and b are swapped, the viewing angle (θ) is mirrored. **(E)** An exemplary height (h) from the eye to a typical *ceiling* and *floor* are displayed [57]. **(F)** The neck tilt angle ranges forwards (blue) and backwards (orange) with the optimal movement range (green) [57]. **(G)** The eye movement and vertical FoV range (blue) with the optimal movement range (green) [57].

3.1 Content Placement Definition

To define the placement of content on the *ceiling* or *floor*, we first describe the relation of the content to the real world before looking at the specific parameters.

Frame of Reference. Regarding the relation to the environment or the user, two reference frames for the content placement can be defined: the *world-* and *body-stabilized* reference frames [7, 15]. In the *world-stabilized*, or exocentric, reference frame, virtual content is connected to an arbitrary object, any other point in the environment, or other persons in the surroundings besides the user. However, with the *body-stabilized*, or egocentric, reference frame, virtual content is attached to the user's body or a particular body part. The content associated with either reference frame follows the same movement as the point of origin of this frame. Following this behavior, the *body-stabilized* reference frame is better suited for private and user-dependent content. In comparison, the *world-stabilized* reference frame is more appropriate for global content or information about the object the reference frame is associated with. In the following, we will only consider the *world-stabilized* reference frame.

Content Placement and Constrains. To define the placement using the *world-stabilized* reference frame (see Fig. A1 in Appendix), we use a Cartesian coordinate system with rotation of pitch (α), roll (β), and yaw (γ), and translation (X, Y, Z) parameters. A more detailed description can be found in Appendix Sec. B.

3.2 Perception, Angular Size, and Viewing Angle

Viewing AR content on the *ceiling* or *floor* (e.g., Fig. 1A) can be affected by perceptual factors, like the distance perception [11] as content could be out-of-view. Therefore, it is necessary to make users aware of such content by notifying or guiding them to it with the help of visual aids (e.g., [5, 22, 48]) or change the distance (d) to the content to support its visibility. Other perceptual factors, such as text perception [20], color perception [35], or visual attention [38], can be of importance as well.

Angular Size. The apparent or angular size (δ) changes depending on the placement parameters, causing hard-to-read content due to the perceived size or higher occlusion of the real-world environment. The angular size (δ) at the eye level can be calculated as follows: $\delta = \arctan(s/2d)$ (see Fig. 2A). However, as soon as content is moved up or down to align it to the *ceiling* or the *floor*, the angular size (δ) changes (see Fig. 2B). To set up an optimal angular size (δ) as seen with the distance-independent millimeter [13], it is possible to manipulate the three placement parameters of distance (d), size (s) of the content, and pitch (α) (see Fig. 2C). To calculate the angular size (δ) of any given 2D content on the *ceiling* or *floor*, the following formula can be used: $\delta = \arccos((a^2 + b^2 - s^2)/2ab)$, where a is the distance to the edge of the content that is connected to either area and b is the distance to the other edge of the content (see Fig. 2D). This calculation is the same for the *ceiling* and the *floor*.

Viewing Angle. While moving content from the eye level of a user to the *floor* or *ceiling*, the viewing angle (θ) of the content also changes (see Fig. 2A and B). This causes virtual content to appear distorted and makes it harder to read and understand the presented information. To increase the visibility and set up an optimal viewing angle (θ), it is again possible to manipulate the three placement parameters of distance (d), size (s), and pitch (α) (see Fig. 2C). To calculate the viewing angle (θ) of any given content on the *ceiling* or *floor*, the following formula can be used: $\theta = \arccos(((s/2)^2 + c^2 - a^2)/sc)$, where a is the distance to the edge where the content connects to either area and c is the distance to the center of the content (see Fig. 2D). For the *ceiling*, the viewing angle (θ) relates to the upper half of the content (see Fig. 2B), while for the *floor*, this angle relates to the lower half.

Differences between Ceiling and Floor. In most cases, the *ceiling* is closer to the head of a user than the *floor* (see Fig. 2E), which lets the viewing direction, as well as the tilt of the neck and eyes differ for both areas. It is easier for humans to look downwards [57], as the ranges for the neck tilt (see Fig. 2F) and eye tilt (see Fig. 2G) downwards are bigger than upwards. Further, the comfort zones for both neck and eye tilts are also in the downwards direction.

3.3 Summary and Study Plans

To address the previously defined research gaps while considering possible content placement challenges on either area, we conducted two user studies. While the first study focuses on generating a general understanding of if and how *ceiling* and *floor* can be used in future AR applications, the second study concentrates on verifying the optimal values for the angular size (δ) and viewing angle (θ).

In the following, we will use the term *secondary* content, which we define as content or information that is not urgent, not prioritized, but can be useful for the user's current primary task or support a secondary task. Additionally, we will also use the term *visual complexity* (VC), which is related to information density, as it is "mainly represented by the perceptual dimensions of quantity of objects [and] clutter" [24], but also "depends on the amount of perceptual grouping an observer perceives in the scene" [45]. Further, VC is related to readability, with regard to our proposed placement parameters, as those alter the perceived size and can introduce distortions.

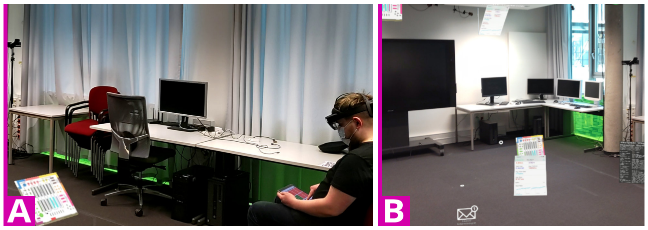

Figure 3: Two scenes of our first study: **(A)** A participant uses a tablet to control a content element. **(B)** Several content elements on the *ceiling* and *floor*, some of which use billboarding.

4 EXPLORATORY USER STUDY

To gain an understanding of the usability of *ceiling* and *floor* as placement areas for AR content, we first conducted an exploratory user study. As our goal was to study how users perceive AR content displayed on both areas in indoor environments, we did not compare these placement areas with the one on users' eye level.

4.1 Design and Methodology

We conducted a semi-structured interview in combination with a think-aloud method using an AR prototype. The interview was split into six different blocks (IB) consisting of two to five different subquestions. Those blocks focused on **(IB1)** the relationship between the distance (d) and content concerning the visual complexity (see Sec. 3.3) and placement area, **(IB2)** the relationship of the distance (d) to public and personal content, **(IB3)** other properties for public and personal content, such as billboarding, **(IB4)** the relationship of posture to the general perception and usability of the placement areas, **(IB5)** interaction with the content placed on the *ceiling* or *floor*, and **(IB6)** questions that focused on the possible use of *ceiling* and *floor*, scenarios, functionalities, ergonomics, and other issues. In general, the experimenter kept a protocol of participants' answers, which was complemented by the recorded audio.

For the study, we described the participants a grocery shopping scenario (see Fig. 1A) to let them envision possible future use cases for AR in their everyday life. Further, this scenario also guided us in creating virtual content, which varies in VC. Beginning with the lowest VC, those are a music app symbol, mail notification symbol with text, grocery shopping list, floor plan for the supermarket, fitness data overview with diagram and text, and a cooking recipe. The interview script, questionnaire, and images of the content elements can be found in the supplementary material.

4.2 Participants

We recruited eight unpaid participants (3 female, 5 male) for our exploratory study. Seven worked as scientific employees at a local university, while one worked as a technician. The age ranged from 25 to 56 years (M=36.25 years, SD=9.45 years), and the self-reported height ranged from 155 to 198 cm (M=176.75 cm, SD=9.45 cm). All participants had normal or corrected-to-normal vision and no color vision defects. On a five-point rating scale, all participants had some experience with AR in general ($M = 2.5, SD = 1.07$), HMD-based AR ($M = 2.63, SD = 1.19$), and virtual reality (VR) ($M = 2.13, SD = 0.99$). The study required no specific previous experience from participants.

4.3 Setup and Apparatus

We conducted the study in a laboratory room with a size of 5.1 m x 8.5 m and a ceiling height of 2.6 m. During the study, participants could either sit on a chair (see Fig. 3A) or move freely through the room, which let them explore the full range of possible postures AR can be used in. As an apparatus, we used a Microsoft *HoloLens 2* worn by the participants, a tablet (Microsoft *Surface Go*) that allows the participants to manipulate the AR content, and a desktop computer running a server for network communication of the devices as well as an application to control the study and log relevant data. We used the Mixed Reality Toolkit (MRTK), Unity 3D, and C# to implement the HoloLens application. To align the virtual content with the real-world study environment, we made use of a QR code[2] scanned at the beginning of the study session. We implemented a web application via JavaScript to remotely control the shown content by placing content on either placement area, changing the shown content element, and placing the content based on the available parameters (see Fig. A1 in Appendix).

For the HoloLens application, we implemented three scenes, each connected to a set of interview blocks. In **Scene 1** (related to IB1 and IB2), a content element was displayed either on the *ceiling* or *floor* at a pitch of 45°. The participants could manipulate the content using the tablet (see Fig. 3A) by altering the placement areas (e.g., pitch), the content elements, or changing the distance to the content between 0 m and 6 m measured from their chair. We used 6 m as the maximum distance to virtual contents considering the vergence-accommodation conflict [42]. In **Scene 2** (related to IB3 and IB4), we presented all six content elements directly on both placement area with a pitch between 45° and 90° (see Fig. 3B). Additionally, billboarding for the yaw (γ) was activated for half of them on either plane. In **Scene 3** (related to IB5), we presented two interaction techniques similar to a semantic zooming approach [25, 36]. Both techniques enabled a change in the detail of the presented content (see Fig. A2 in Appendix). In the default state, only a mail icon or meal images are visible. Triggered by either gaze (dwell time) or proximity (less than 1.5 m), the shown content changed its pitch from 0° to 90° while exchanging the content to a subject and first two lines of the mail or a user rating. Lastly, the complete mail or recipe could be accessed by an air-tap on the content, which brought it to the usual eye level.

4.4 Procedure

After getting acquainted with the purpose of the study, participants signed the consent form and filled out a questionnaire about demographic data and technology familiarity. Afterward, the experimenter presented the grocery shopping scenario, guided the participants to wear a HoloLens 2 and perform the eye calibration for a better viewing experience. Next, participants were asked to scan a QR code placed on a table in the room to fix the world-stabilized coordinate system. The participants then started the web application on the tablet, while the experimenter started the server and the study control application. During the main part of the study, participants experienced all three scenes in ascending order. The participants were instructed to think aloud while exploring the scenes and answering the interview questions, which were also used to guide the participants through the application. The participants were encouraged to sit on the chair, stand, or walk inside the study environment throughout the whole study session, while at the beginning of the experiment, participants were sitting. The main part of the study lasted approximately 59 min (M=59:26 min, SD=6:51 min).

4.5 Study Results

We analyzed 484 notes collected from participants (P) through an affinity diagramming [23] approach. We created four overarching thematic groups focusing on placement areas, content types and their placement, interaction and functionalities, ergonomics and postures.

Placement Areas. In general, the *ceiling* and the *floor* were perceived to be suitable exclusively as a secondary information display (P1, P2, P4, P5, P7, P8), i.e., for easily and quickly digestible content that does not take up the user's main attention. While four participants preferred displaying AR content on the *floor* (P3, P6-8), one favored the *ceiling* (P5). Participants highlighted that content placed on the *floor* can be perceived as obstacles (P1, P3-5, P7)

---

[2] `www.nuget.org/Packages/Microsoft.MixedReality.QR`

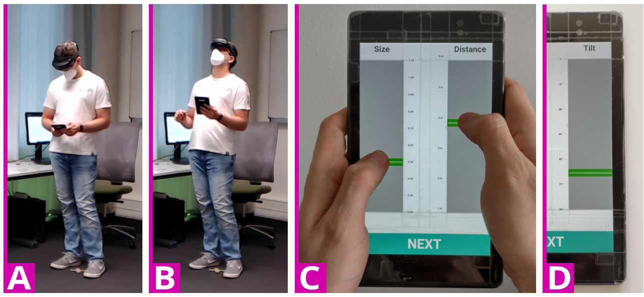

Figure 4: The second study setup. **(A)** and **(B)** show a participant looking at content displayed on the *floor* and *ceiling* respectively at a distance of $d = 1\ m$ (Part 3). **(C)** and **(D)** show the tablet the participants used to alter two placement parameters of the study.

that can limit movement (P5). However, placing a content flat on the ground ($pitch = 0^\circ$) might be perceived as a "sticker" (P5) and reduce the "respect" for this content (P5, P7). Some participants were also concerned that the virtual content might occlude physical objects in the environment, such as signs on the *floor* (P2, P5, P7, P8). Furthermore, participants indicated that by getting familiar with the *ceiling* and some training, possible out-of-view problems could be resolved (P1, P3, P6, P7). Moreover, it was also mentioned that a quick look at the *ceiling* to check secondary content such as a notification is a "reduction of movement" (P7) compared to taking a smartphone in hand and unlocking it.

Content Types and their Placement. As participants spoke about their preferred content types, six participants (P1-4, P7, P8) favored abstract and less complex information on the *ceiling* while five participants (P2-4, P7, P8) preferred detailed and therefore more complex information on the *floor*. Three participants (P6-8) stated that the content on the *floor* should be displayed close to the user. This is also the case for content with more information, as mentioned by seven participants (P1-5, P7, P8). Lastly, five participants (P1, P2, P6-8) preferred content on the *ceiling* to be farther away, which shows the overall wish to reduce the uncommon upward head movements.

Interactions and Functionalities. A simple head movement up or down allows the users to access the content on either area. This was deemed enough for two participants (P2, P8), while two others (P5, P6) stated a need for additional interaction techniques. In the second scene, participants commented that the billboarding effect was an "attention catcher" (P4, P5, P7), which distracted some participants (P2, P5, P8). For the third scene, both used interaction techniques were rated as beneficial (Gaze: P1, P3-6, P8; Proximity: P1-6). Lastly, all participants liked the possibility of bringing virtual content to their eye level on demand.

Posture and Ergonomics. Three participants (P1, P2, P7) stated that they prefer standing as it promotes physical navigation. Additionally, two participants (P4, P6) mentioned that while standing, the *floor* was more uncomfortable since it had become farther away, while the *ceiling* was better to use for more distant content (P4). Regarding the ergonomics, four participants (P1, P3, P6, P7) found looking at the *ceiling* for an extended time exhausting. In contrast, one participant found the weight of the *HoloLens 2* exhausting for looking at the *floor*. Five participants (P1, P4, P6-8) did not see any problem with ergonomics as long as the areas were mainly used for secondary content presentation.

4.6 Discussion

While our results showed that *ceiling* and *floor* are promising placement areas, users might miss content there due to out-of-eye-level placement. Participants reported that they could easily access this kind of content with a short head movement. Moreover, our results suggest that content on the *ceiling* should be abstract and displayed further away, and more detailed content should be placed closer on the *floor*. This can be explained by the need to reduce long uncommon upward head movements. Participants were also concerned with occlusion and less visible content placement issues on the *ceiling* and *floor*. These issues can be resolved by changing the distance (d) to the user or altering the pitch (α) of virtual content on these areas. However, the preferable parameters of virtual content placement above on the *ceiling* and below on the *floor* remain unclear.

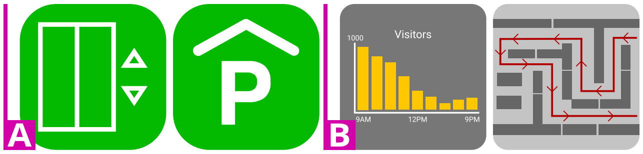

Figure 5: Exemplary **(A)** *low* and **(B)** *medium* VC content elements.

5 USER STUDY: PLACEMENT OF CONTENT

The results of our exploratory user study show that both the *ceiling* and *floor* are promising secondary content placement areas. As the participants explored both areas, they preferred viewing while standing and different amount of information. With this in mind, we conducted a second study to investigate the preferred placement of different content types on either area. In this study, we asked participants to adjust the placement parameters of distance (d), pitch (α), and content size (s). Through the study, we aimed to address the following research questions: **RQ1**: Is it preferred to have a viewing angle (θ) of 90°, which is perpendicular to the viewing direction? **RQ2**: Are there any differences regarding the user-defined content placement depending on visual complexity levels? **RQ3**: Are there any differences regarding *ceiling* and *floor* regarding the user-defined content placement?

5.1 Design and Methodology

We conducted a within-subjects user study with two independent variables: placement area (*ceiling* and *floor*) and visual complexity (*low* and *medium*). While for *low* visual complexity (VC), we used content with an iconic representation that can be very quickly perceived, for *medium* VC, we presented combinations of several icons, shapes, or texts. This decision is in line with the results of our first study, as it suggests the use of content that does not require immediate attention. Further, we did not include high VC content (e.g., a recipe), as such content could require a longer duration to perceive and hinder users from their primary task [56]. Motivated by the grocery shopping scenario, we created a set of 20 different instances of each VC level, e.g., arrow and elevator signs as *low* VC and location plan and product comparison as *medium* VC contents (see Fig. 5B and Fig. 1B).

Our five dependent variables were the distance (d) from content to the user, pitch (α) of the content, content size (s), as well as the angular size (δ) and viewing angle (θ) as compound values formed from the previous three parameters (see Sec. 3.2). In this study, each participant performed 120 trials, wherein two placement parameters could be freely controlled within a predefined range, while the third one was selected from a set of five predefined instances for every trial. Similar to the previous work [13], we fixed the third parameter since the parameters were related to each other. Considering the design guidelines for a comfortable content **distance (d)** range of 1.25 m to 5 m [42], we selected a range of 1 m to 6 m, in combination with five instances of the distance as 1 m, 2.25 m, 3.5 m, 4.75 m, and 6 m. Regarding the **pitch (α)**, we used a range from 0° to 90° (see Appendix Sec. C). Again, we additionally selected five fixed instances of the pitch by splitting the range into equal pieces: 0°, 22.5°, 45°, 67.5°, and 90°. Lastly, to define a square content element's **size (s)**, we conducted a small experiment with six participants. Here, participants used a HoloLens 2 to define the biggest and smallest sizes of visible test content displayed at distances of

Table 1: ANOVA main effects and interactions for the angular size (δ) and viewing angle (θ). Statistically significant effects ($p < 0.05$) are highlighted in green. With VC = visual complexity level.

Condition	Angular Size (δ)			Viewing Angle (θ)		
	$F_{1,25}$	**p**	η_p^2	**$F_{1,25}$**	**p**	η_p^2
Area	0.896	0.353	0.035	1.691	0.205	0.063
VC	124.185	< 0.0001	0.832	26.610	< 0.0001	0.519
Area x VC	0.004	0.945	0.000	9.073	< 0.01	0.266

1 m and 6 m on their eye level. This generated an average range from 0.2 m to 1.1 m. Using this range, we defined the instances for the size as 0.2 m, 0.425 m, 0.65 m, 0.875 m, and 1.1 m.

For each study session, we logged the preferred placement parameters to calculate the angular size (δ) and viewing angle (θ) (see Sec. 3.2). We also used questionnaires to collect demographic data and information about participants' height, their health state before and after the study, their strategies for adjusting the available placement parameters (e.g., "Did you have a special procedure for setting the parameters?"), and their placement preferences (e.g., "Which parameter was most important for you?"). The questionnaire, content elements, collected data, and analysis scripts can be found in the supplementary material.

5.2 Participants

We recruited 26 participants (7 female, 19 male) who were compensated with 10€. All participants had a technical background and were either studying or working at the local university. The age ranged from 20 to 42 years (M=26.04 years, SD=4.82 years), and the self-reported height ranged from 155 to 198 cm (M=176.19 cm, -SD=10.08 cm). All participants had normal or corrected-to-normal vision. Two participants indicated having a color deficiency, while one had slight spatial perception problems. On a five-point rating scale, all participants had some experience with AR in general ($M = 2.54, SD = 1.21$), HMD-based AR ($M = 2.07, SD = 1.09$), and VR ($M = 2.07, SD = 1.09$). As in the first study, no specific experience was required for participation.

5.3 Setup and Apparatus

For this study, we used the same prototype, apparatus, and room as described in our first study (see Sec. 4.3). However, we made several changes to fit the study design. During the study, participants stood at a predefined position in the room while using a HoloLens 2 application (see Fig. 4A and B). The application displayed virtual content on either placement area, and participants could manipulate it using sliders on the tablet (see Fig. 4C and D). We also changed the UI of the web app to allow controlling two parameters via sliders on the tablet (Asus Nexus 7) and advancing to the subsequent trial with a "Next" button on the bottom of the screen. To avoid the effect of using the tablet on our results, we added a transparent tape on the screen to help participants easily locate the sliders and the button without looking at the tablet (see Fig. 4C and D). To present the questionnaires, we used LimeSurvey.

5.4 Task

The presented task was formulated as: "Place the visible content with the available parameters in such a way that they are optimal and best perceivable for you". Within the task, the participants should focus on their subjective perception and placement strategies, which we later gathered via the questionnaires. We created three parts, in which the participants were only able to control two of the three placement parameters (see Fig. 4C and D). In **Part 1**, the distance (d) and pitch (α), in **Part 2**, the distance (d) and size (s) (see Fig. 4C), and in **Part 3**, the pitch (α) and size (s) were controllable within their ranges, while for the remaining parameter, we used one of the five fixed instances in each trial. This allowed us to collect data for all values on our predefined range and verify the relation between different values of the same parameter. Overall, each participant had to perform 40 trials per part (2 placement areas × 2 VC × 5 fixed-parameter instances × 2 repetitions), resulting in 120 trials per participant. We altered the used placement area after every ten trials to reduce a potential neck strain. To reduce the possible effects of the order of parts and trials, we randomized the order of the parts via a Latin square. Furthermore, the order of trials (fixed-parameter instances × VC) and the start values for the two controllable parameters in each trial were completely randomized.

Table 2: Mean (M) and standard deviation (SD) values of each placement and the derived parameters. For each placement parameter, we removed the trials with fixed values. With F = *floor*, C = *ceiling*, VC = visual complexity level, L = *low*, and M = *medium*.

Condition		d in m		α in $^\circ$		s in m		δ in $^\circ$		θ in $^\circ$	
Area	VC	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
C	L	4.46	1.34	68.4	19.5	0.47	0.20	6.63	3.96	73.1	24.5
C	M	3.46	1.37	68.0	17.5	0.74	0.22	10.2	4.23	73.6	22.2
F	L	4.06	1.44	49.4	29.5	0.48	0.19	6.46	3.57	71.5	26.2
F	M	3.09	1.33	55.8	21.9	0.71	0.20	10.01	3.9	78.2	20.4
C		3.96	1.47	68.2	18.5	0.60	0.25	8.42	4.47	73.3	23.4
F		3.57	1.47	52.6	26.1	0.60	0.23	8.21	4.16	74.9	23.7
	L	4.26	1.43	58.9	26.7	0.48	0.20	6.54	3.77	72.3	25.4
	M	3.27	1.36	61.8	20.7	0.72	0.21	10.1	4.09	75.9	21.4

5.5 Procedure

After the participants filled out a consent form and a questionnaire about demographics and technology familiarity, they were introduced to the grocery shopping scenario. Next, participants stood in the predefined location in the room, and we helped them wear the HoloLens 2, perform the eye calibration on the device, and start the mobile study application on the tablet. Afterward, we asked participants to scan a QR code placed on a table in the room to fix the world-stabilized coordinate system, which was repeated in each study part. A short training session was conducted before the participants performed the task with the three parts as mentioned above. After each part, participants filled out a questionnaire to indicate their content placement strategy. While filling out the questionnaire, participants set down the HoloLens 2 to recover from possible neck strains. At the end of the study, the participants indicated their preferences regarding the placement areas and provided general feedback. The main part of the study, without filling out the questionnaires, lasted approximately 23 min (M=23:25 min, SD=6:08 min).

5.6 Study Results

We collected data from 3120 trials. We removed 37 trials (1.18%) due to technical reasons (i.e., unintentional double click on the "Next" button on the tablet), which were detected by comparing start and end time, as well as start and submitted value of the trial. We calculated the angular size (δ) and viewing angle (θ) using the formulas presented in Fig. 2D. Moreover, we subtracted 11.2 cm from the participants' body height to calculate the distance from the ground to the participant's eyes, as suggested by Tiley [57]. Additional to the quantitative logged data of the trials, the questionnaires provided us with 304 comments, which we sorted by affinity diagramming [23].

Angular Size and Viewing Angle. We performed two-way repeated-measures ANOVAs (see Tab. 1) on angular size (δ) and viewing angle (θ), which show that VC statistically significantly affects both values. Moreover, there was an interaction effect between the placement area and VC for the viewing angle, also visible in Tab. 2, as well as in Fig. 6. In general, the contents with *low* VC were set to a lower angular size (δ) ($M = 6.5^\circ, SD = 3.8^\circ$) than those with *medium* VC ($M = 10.1^\circ, SD = 4.1^\circ$). This shows that with a growing amount of information on a content element, the apparent size (δ)

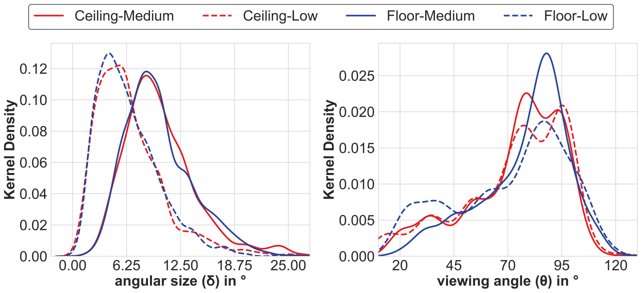

Figure 6: A kernel density estimation plot for both the angular size (δ) and viewing angle (θ).

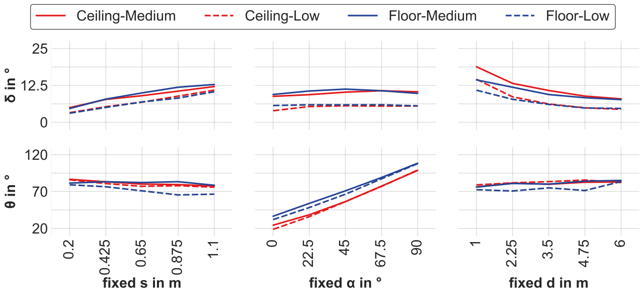

Figure 7: Overview how angular size (δ) and viewing angle (θ) changed with regard to the fixed parameter instances (5 per x axis).

of this content should also increase. Additionally, the viewing angle (θ) for content with *low* VC was smaller ($M = 72.3°, SD = 25.4°$) than for those with *medium* VC ($M = 75.9°, SD = 21.4°$). The bigger standard deviation for *low* VC content in combination with the wider distribution of the viewing angle (θ) in Fig. 6 (another peak at around 30° for *low* VC content) shows that the viewing angle (θ) for *low* VC is usable in a more flexible manner. Furthermore, 5 participants stated that they are far more tolerant towards imperfect viewing angles on the *floor* compared to the ones on the *ceiling*.

Placement Parameters. With our study design, participants had to compensate for a non-adjustable parameter to achieve optimal angular size (δ) or viewing angle (θ). 14 participants also reflected on this behavior in the questionnaire. While pitch (α) had the most considerable influence on the viewing angle (θ) (Fig. 7, middle column), the differences between *low* and *medium* VC content in the Part 3 (Fig. 7, right column) increased faster over the fixed distances (d) to achieve a bigger angular size (δ).

Descriptive statistics (see Tab. 2) show the following behavior partly supported by participants' comments. Participants placed content on the *ceiling* farther away ($M = 3.96\,m, SD = 1.47\,m$) than the content on the *floor* ($M = 3.57\,m, SD = 1.47\,m$) which was supported by participants comments (5 out of 26). Content with *low* VC was also placed farther away ($M = 4.26\,m, SD = 1.43\,m$) while having a smaller size ($M = 0.48\,m, SD = 0.2\,m$), compared to the *medium* VC content, which was closer ($M = 3.27\,m, SD = 1.36\,m$) and bigger in size (s) ($M = 0.72\,m, SD = 0.21\,m$). The behavior regarding the content with *low* VC was confirmed by 10 participants. Lastly, the content on the *ceiling* had a bigger pitch (α) ($M = 68.2°, SD = 18.5°$) than the content on the *floor* ($M = 52.6°, SD = 26.1°$). Participants also commented on placement parameter values. While 10 participants stated that content on the *ceiling* should have a 90° pitch (α), 6 participants reported that the content on the *floor* should be at 0° pitch (α). Furthermore, participants mentioned that smaller content should be displayed closer (7 out of 26) and bigger content farther away (7 out of 26) from the user. Lastly, 12 participants described a relation between the pitch (α) and the distance (d) parameters by stating that a smaller pitch (α) led to closer content and vice versa. Similarly, for 6 participants, a bigger pitch (α) led to further away content.

Participants' Goal and Preferences. To the question of which parameter was most important for the placement, 11 voted for distance (d), 10 preferred pitch (α), and 5 indicated size (s). 24 participants stated that they aimed to achieve the most readable and visible content. This includes participants' wish to see the content as straight and undistorted as possible (14 out of 26) while not overfilling their and the HoloLens' FoV (9 out of 26). Furthermore, most participants tried to minimize the neck strain while optimizing the ergonomics of the placed content (21 out of 26). 10 participants also stated that it is more pleasant to look at content on the *floor* than on the *ceiling*, which is related to the bending range of the neck and the eyes (see Fig. 2F and G).

Furthermore, placement preferences were influenced based on the real-world environment (9 out of 26) or the meaning and context of the presented content (8 out of 26) (e.g., maps for orientation). For example, to simulate signage hanging from the *ceiling* in the real world, 10 participants placed the content with a 90° pitch (α). On the other hand, 6 participants placed the content on the *floor* with a 0° pitch (α) to simulate a guiding arrow on the streets. However, 5 participants stated that they would rather keep the *floor* as free as possible as they would perceive the content on it as an obstacle.

5.7 Discussion

Following, we discuss the results of our second study by addressing our three research questions (see Sec. 5.1).

RQ1: Is a viewing angle (θ) of 90° preferred? RQ1 was not confirmed as the results showed that the mean values (see Tab. 2) for the viewing angle (θ) were lower than 90°. This can be explained by the fact that trials with fixed pitch (α), which has the most significant influence on the viewing angle (θ) (see Fig. 2C and Fig. 7 middle column), are considered for the mean values. Overall, the participants strived for 90° of viewing angle (θ) on both areas, however, due to preferences, this was not always achieved. For example, they placed the content on the *floor* flat ($\alpha = 0°$), which reduced the viewing angle (θ), or hung from the *ceiling* like signage ($\alpha = 90°$), which increased the viewing angle (θ) above 90° (see Fig. 6).

RQ2: Differences in content placement regarding visual complexities? Our results show a difference in the preferred angular size (δ) and viewing angle (θ) for the content on the *ceiling* and *floor* (see Tab. 1 and Fig. 6). Participants preferred a bigger angular size (δ) and viewing angle (θ) for medium VC content than low VC.

RQ3: Differences in content placement regarding both areas? Our data show several differences with regard to the content placement on the *ceiling* and *floor* (see Tab. 2). Participants manipulated the placement parameters differently to achieve a similar angular size (δ) on both areas. However, while viewing angles (θ) were similar for contents on the *ceiling*, participants set a bigger viewing angle (θ) for the medium VC content than the low one on the *floor*.

6 OVERALL DISCUSSION

The findings of our two user studies (S1 and S2) showed how the *ceiling* and the *floor* can be used for AR content placement in indoor environments. Following, we discuss overall findings and present design recommendations and future research directions.

6.1 Result Discussion

With S2, we showed that content placement on the *ceiling* and *floor* is governed by the wish for an optimal viewing angle (θ) and angular size (δ). Through S1, we showed that the VC should be considered while placing content in these areas. In general, we found that secondary content (e.g., non-urgent short text notes, icons) was deemed suitable for use in both areas, while primary content (e.g., compelling text-heavy content) should be avoided (S1: 6/8). Both findings can further be motivated by the two goals the participants described: the ergonomics of finding and reading the content (S1: 6/8, S2: 21/26) and the readability of the content itself (S2: 24/26). The trial duration in S2 differentiated between both VC levels ($F(1,25) = 23.95, p < 0.001, \eta_p^2 = 0.489$), whereof trials with *low* VC content ($M = 10.78\ sec, SD = 7.07\ sec$) were faster than those with *medium* VC content ($M = 12.24\ sec, SD = 7.80\ sec$). This shows that low VC content was easier to place, which can be explained by the decreasing complexity, increasing readability, and even the higher tolerance for the low VC content in general.

Another factor that influences the readability and the ergonomics is the area of content placement. Based on a seven-point rating scale (-3 to 3) in S2, we found that participants prefer *low* VC content to be placed on the *ceiling* ($M = -0.0653, SD = 1.648$) and *medium* VC content on the *floor* ($M = 0.577, SD = 1.858$). Through the comments in S1, this preference of placing *low* VC content on the *ceiling* (S1: 6/8) and *medium* VC content on the *floor* (S1: 5/8) can be further strengthened. In general, the *floor* (S1: 5/8) is more preferable for content placement than the *ceiling* (S1: 1/8), as it is more comfortable to look downwards (S2: 10/26) than upwards (S2: 2/26). However, the longer, continuous, and more focused use of both areas, as presented in S2, showed a small negative effect on the users. This is visible by comparing the 5-point rating scale answers for the question "How strained is your neck?" ($t(25) = -5.52, p < 0.0001, d = 0.87$) before ($M = 1.462, SD = 0.582$) and after ($M = 2.231, SD = 1.107$) the study.

6.2 Design Recommendations

With our findings, we present an initial set of recommendations for designing future user interfaces displaying 2D AR content on the *ceiling* and *floor* within simple physical environments.

DR1 As ceiling and floor are unobtrusive locations, these areas should be mainly used to display secondary information.

DR2 Both placement areas should be used for different types of content: the *ceiling* mainly for *low* VC content and the *floor* for *medium* VC content. This can be explained by the increased neck strain while locking upwards and the more comfortable downwards movement range.

DR3 Content on the *floor* could be perceived as obstacles hindering users' general movement. We, therefore, recommend minimizing the use of pitch (α) and distance from the *floor* (height (Z), see Fig. A1 in Appendix), which can be perceived as 3D content.

DR4 In environments constraining the availability of specific placement parameters, it is possible to adjust the angular size (δ) and the viewing angle (θ) to achieve an optimal content placement by employing the other available placement parameters (see Fig. 2).

DR5 The angular size (δ) of a virtual content should increase in relation to its VC. Generally, we recommend an angular size of $\delta \approx 6.5°$ for *low* VC and of $\delta \approx 10°$ for *medium* VC content.

DR6 Content should be placed as undistorted as possible (viewing angle $\theta = 90°$). However, specific user preferences should be considered first, like the placement of flat stickers on the *floor* ($\alpha = 0°$) or signage hanging from the *ceiling* ($\alpha = 90°$).

6.3 Future Work and Limitations

Based on our findings, we can envision that future AR systems could automatically adjust the content placed on the *ceiling* or *floor*. However, it is unclear how users of such applications would perceive dynamically changing virtual objects. Future research is needed to investigate if this adaptation would distract the users while interacting with the real world or other virtual content placed in the environment. The static setup in our second study (i.e., standing participants) helped us to reduce possible confounding factors while setting optimal placement parameters. Examples of static setup can be looking at art pieces in a museum or the schedule in the train station. However, dynamic environments or even participants' movements can cause a difference in the observed preferences, which shows the need for future research in this direction. Furthermore, this can also be extended to altering *ceiling* heights, but also the heights of the person, which can already differ for each user individually, as they change their posture from, e.g., standing to sitting. Additionally, although our grouping of the virtual content via visual complexity was loosely defined on information density and readability, we already found statistically significant effects. We assume that using a content element with higher visual complexity would amplify this effect. Further, a more in-depth understanding of different aspects of content will be beneficial for future systems.

The environment can also heavily influence how users perceive virtual and real-world content. While our participants considered virtual content occluding real-world signage on the *floor* as an issue (S1: 4/8, S2: 5/26), they also mentioned that the same virtual content, if not flat on the *floor* ($\alpha = 0°$), could be perceived as an obstacle (S1: 5/8). Therefore, we suggest researchers investigate how content placed on both areas changes user behavior and the perception of the real-world environment. As the environment can also affect the placement of the content (S2: 9/26), it is necessary to investigate the effect of *ceiling* and *floor* textures, environmental factors, contexts, or use cases, which can also be extended to not only indoor but also outdoor scenarios. Lastly, we believe that our findings for the *world-stabilized* placement can be translated to *body-stabilized* reference frames, however, this should be verified in the future.

To conduct the studies, we used the Mircosoft HoloLens 2 as a state-of-the-art AR HMD. However, the current technology is still rather limited, especially concerning the resolution and FoV. Therefore, we expect some specific findings to change slightly if the same experiments were repeated on more advanced hardware. Through a higher resolution, the same content can be perceivable on even greater distances (d) than 6 m, which can be especially distinct for text-heavy elements, while at the same time a bigger FoV allows easier access to content as the required head movement can be reduced. However, we would still assume that users would aim for a constant angular size (δ) and viewing angle (θ) as shown with our results, which in turn would affect the placement parameters in the same way. Another issue considering the used HMD could arise while rendering oblique content due to low rendering quality or limited resolution, which requires further investigation.

7 CONCLUSION

With two user studies, we investigated *ceiling* and *floor* as additional 2D content placement areas for indoor AR applications. The results of our exploitative study show the applicability of the two placement areas as a secondary display space for virtual AR content. In addition, the second study allowed us to define optimal placement parameters for 2D virtual content on either area. Following our findings, we presented an initial set of recommendations that can benefit future AR application designers and open up research questions. We envision that both the *ceiling* and the *floor* will become an indispensable part of future AR systems and user interfaces. However, further research has to be conducted to achieve this considering, e.g., texture in placement areas, objects in the environment, moving users of AR systems, or even other content types. In conclusion, we hope to have laid the foundations for the use of *ceiling* and *floor* for AR content placement and to help researchers and developers consider both areas when developing future indoor AR applications.

ACKNOWLEDGMENTS

The authors thank Mats Ole Ellenberg, Ricardo Langner, and Wolfgang Büschel for their valuable feedback. This work was funded by the Deutsche Forschungsgemeinschaft (DFG) grant 319919706/RTG 2323, grant 389792660 as part of TRR 248 (see `https://perspicuous-computing.science`), and as part of Germany's Excellence Strategy Cluster of Excellence – EXC-2050/1 – 390696704 – "Centre for Tactile Internet with Human-in-the-Loop" and – EXC-2068 – 390729961 – "Physics of Life" of TU Dresden.

REFERENCES

[1] J. Ahn, J. Williamson, M. Gartrell, R. Han, Q. Lv, and S. Mishra. Supporting healthy grocery shopping via mobile augmented reality. *ACM Trans. Multimedia Comput. Commun. Appl.*, 12(1s), oct 2015. doi: 10.1145/2808207

[2] R. Azuma, Y. Baillot, R. Behringer, S. Feiner, S. Julier, and B. MacIntyre. Recent advances in augmented reality. *IEEE Computer Graphics and Applications*, 21(6):34–47, 2001. doi: 10.1109/38.963459

[3] R. Azuma and C. Furmanski. Evaluating label placement for augmented reality view management. In *The Second IEEE and ACM International Symposium on Mixed and Augmented Reality*, pp. 66–75. IEEE Comput. Soc, 2003. doi: 10.1109/ISMAR.2003.1240689

[4] J. L. V. Barbosa. Ubiquitous computing: Applications and research opportunities. In *2015 IEEE International Conference on Computational Intelligence and Computing Research, ICCIC 2015*, 2016. doi: 10.1109/ICCIC.2015.7435625

[5] P. Baudisch and R. Rosenholtz. Halo: A technique for visualizing off-screen locations. In *Conference on Human Factors in Computing Systems - Proceedings*, pp. 481–488, 2003.

[6] B. Bell, S. Feiner, and T. Höllerer. View management for virtual and augmented reality. In *Proceedings of the 14th Annual ACM Symposium on User Interface Software and Technology*, UIST '01, p. 101–110. Association for Computing Machinery, New York, NY, USA, 2001. doi: 10.1145/502348.502363

[7] M. Billinghurst, J. Bowskill, M. Jessop, and J. Morphett. A wearable spatial conferencing space. In *Digest of Papers. Second International Symposium on Wearable Computers (Cat. No.98EX215)*, vol. 1998-Octob, pp. 76–83. IEEE Comput. Soc, 1998. doi: 10.1109/ISWC.1998.729532

[8] M. Billinghurst, A. Clark, and G. Lee. A Survey of Augmented Reality. *Foundations and Trends® in Human–Computer Interaction*, 8(2-3):73–272, 2015. doi: 10.1561/1100000049

[9] W. Büschel, A. Mitschick, and R. Dachselt. Here and Now: Reality-Based Information Retrieval Wolfgang. In *Proceedings of the 2018 Conference on Human Information Interaction&Retrieval - CHIIR '18*, pp. 171–180. ACM Press, New York, USA, 2018. doi: 10.1145/3176349.3176384

[10] A. Colley, L. Ventä-Olkkonen, F. Alt, and J. Häkkilä. Insights from deploying see-through augmented reality signage in the wild. In *PerDis 2015 - Proceedings: 4th ACM International Symposium on Pervasive Displays*, pp. 179–185. ACM Press, New York, USA, 2015. doi: 10.1145/2757710.2757730

[11] J. E. Cutting and P. M. Vishton. Perceiving Layout and Knowing Distances : The Integration, Relative Potency, and Contextual Use of Different Information about Depth. In W. Epstein and S. Rogers, eds., *Perception of Space and Motion*, vol. 22, chap. 3, pp. 69–117. Academic Press, 1995.

[12] A. Dancu, Z. Franjcic, A. A. Ünlüer, and M. Fjeld. Interaction in motion with mobile projectors: Design considerations. In *PerDis 2015 - Proceedings: 4th ACM International Symposium on Pervasive Displays*, pp. 61–68. ACM, New York, USA, 2015. doi: 10.1145/2757710.2757728

[13] T. Dingler, K. Kunze, and B. Outram. VR reading UIs: Assessing text parameters for reading in VR. In *Conference on Human Factors in Computing Systems - Proceedings*, vol. 2018-April. Association for Computing Machinery, 2018. doi: 10.1145/3170427.3188695

[14] N. A. Elsayed, C. Sandor, and H. Laga. Visual Analytics in Augmented Reality. In *2013 IEEE International Symposium on Mixed and Augmented Reality, ISMAR 2013*, pp. 1–4. IEEE, 2013. doi: 10.1109/ISMAR.2013.6671817

[15] B. Ens, J. D. Hincapié-Ramos, and P. Irani. Ethereal Planes: A Design Framework for 2D Information Spaces in 3D Mixed Reality Environments. In *Proceedings of the 2nd ACM symposium on Spatial user interaction - SUI '14*, pp. 2–12. ACM Press, New York, USA, 2014. doi: 10.1145/2659766.2659769

[16] A. Erickson, K. Kim, G. Bruder, and G. Welch. A Review of Visual Perception Research in Optical See-Through Augmented Reality. *ICAT-EGVE*, pp. 1–9, 2020. doi: 10.2312/egve.20201256

[17] J. Franz, J. Malloch, and D. Reilly. Compensating for Perspective-based Distortion on Large Interactive Floor Displays: The SpaceHopper Field Experiment. In *IMX 2020 - Proceedings of the 2020 ACM International Conference on Interactive Media Experiences*, vol. 20, pp. 45–54. Association for Computing Machinery, Inc, New York, USA, 2020. doi: 10.1145/3391614.3393651

[18] M. Friedewald and O. Raabe. Ubiquitous computing: An overview of technology impacts. *Telematics and Informatics*, 28(2):55–65, 2011. doi: 10.1016/j.tele.2010.09.001

[19] M. Funk, A. Bächler, L. Bächler, O. Korn, C. Krieger, T. Heidenreich, and A. Schmidt. Comparing projected in-situ feedback at the manual assembly workplace with impaired workers. In *8th ACM International Conference on PErvasive Technologies Related to Assistive Environments, PETRA 2015 - Proceedings*. ACM, 2015. doi: 10.1145/2769493.2769496

[20] M. Gattullo, A. E. Uva, M. Fiorentino, and G. Monno. Effect of Text Outline and Contrast Polarity on AR Text Readability in Industrial Lighting. *IEEE Transactions on Visualization and Computer Graphics*, 21(5):638–651, 2015. doi: 10.1109/TVCG.2014.2385056

[21] J. Grubert, T. Langlotz, S. Zollmann, and H. Regenbrecht. Towards pervasive augmented reality: Context-awareness in augmented reality. *IEEE Transactions on Visualization and Computer Graphics*, 23(6):1706–1724, 2017. doi: 10.1109/TVCG.2016.2543720

[22] U. Gruenefeld, A. E. Ali, W. Heuten, and S. Boll. Visualizing out-of-view objects in head-mounted augmented reality. In *Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services*, MobileHCI '17. Association for Computing Machinery, New York, USA, 2017. doi: 10.1145/3098279.3122124

[23] G. Harboe and E. M. Huang. Real-world affinity diagramming practices: Bridging the paper-digital gap. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, p. 95–104. Association for Computing Machinery, 2015. doi: 10.1145/2702123.2702561

[24] S. Harper, E. Michailidou, and R. Stevens. Toward a definition of visual complexity as an implicit measure of cognitive load. *ACM Transactions on Applied Perception*, 6(2), 2009. doi: 10.1145/1498700.1498704

[25] C. Harrison and A. K. Dey. Lean and Zoom: Proximity-aware user interface and content magnification. In *Conference on Human Factors in Computing Systems - Proceedings*, pp. 507–510, 2008. doi: 10.1145/1357054.1357135

[26] S. Hirai and M. Takamura. Everyday Life ToDo Display on Ceiling for Smart Living Space. In *2019 IEEE International Conference on Pervasive Computing and Communications Workshops, PerCom Workshops 2019*, pp. 239–242, 2019. doi: 10.1109/PERCOMW.2019.8730584

[27] S. Imamov, D. Monzel, and W. S. Lages. Where to display? How Interface Position Affects Comfort and Task Switching Time on Glanceable Interfaces. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 851–858. Institute of Electrical and Electronics Engineers (IEEE), 2020. doi: 10.1109/VR46266.2020.00012

[28] K. Kim, M. Billinghurst, G. Bruder, H. B. L. Duh, and G. F. Welch. Revisiting trends in augmented reality research: A review of the 2nd Decade of ISMAR (2008-2017). *IEEE Transactions on Visualization and Computer Graphics*, 24(11):2947–2962, 2018. doi: 10.1109/TVCG.2018.2868591

[29] M. Kim, K. B. Park, S. H. Choi, J. Y. Lee, and D. Y. Kim. AR/VR-based live manual for user-centric smart factory services. In *IFIP Advances in Information and Communication Technology*, vol. 536, pp. 417–421. Springer New York LLC, 2018. doi: 10.1007/978-3-319-99707-0_52

[30] E. M. Klose, N. A. Mack, J. Hegenberg, and L. Schmidt. Text presentation for augmented reality applications in dual-task situations. In *26th IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2019 - Proceedings*, pp. 636–644. Institute of Electrical and Electronics Engineers Inc., 2019. doi: 10.1109/VR.2019.8797992

[31] E. Kruijff, J. E. Swan, and S. Feiner. Perceptual Issues in Augmented Reality Revisited. In *9th IEEE International Symposium on Mixed and Augmented Reality 2010: Science and Technology, ISMAR 2010 - Proceedings*, pp. 3–12. IEEE, 2010. doi: 10.1109/ISMAR.2010.5643530

[32] R. Langner, M. Satkowski, W. Büschel, and R. Dachselt. MARVIS: Combining Mobile Devices and Augmented Reality for Visual Data Analysis. In *Conference on Human Factors in Computing Systems -*

Proceedings. ACM, New York, NY, USA, 2021. doi: 10.1145/3411764.3445593

[33] G. Li, Y. Liu, and Y. Wang. An empirical evaluation of labelling method in augmented reality. In *Proceedings - VRCAI 2018: 16th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and its Applications in Industry*. Association for Computing Machinery, Inc, 2018. doi: 10.1145/3284398.3284422

[34] N. Liberati. Augmented reality and ubiquitous computing: the hidden potentialities of augmented reality. *AI and Society*, 31(1):17–28, 2016. doi: 10.1007/s00146-014-0543-x

[35] M. A. Livingston, J. L. Gabbard, J. E. S. Ii, C. M. Sibley, and J. H. Barrow. Basic Perception in Head-Worn Augmented Reality Displays. In *Human Factors in Augmented reality environments*, pp. 35–65. Springer, New York, 2013. doi: 10.1007/978-I-461

[36] J. Looser, M. Billinghurst, and A. Cockburn. Through the looking glass: The use of lenses as an interface tool for augmented reality interfaces. In *Proceedings GRAPHITE 2004 - 2nd International Conference on Computer Graphics and Interactive Techniques in Australasia and Southeast Asia*, pp. 204–211. ACM Press, New York, USA, 2004. doi: 10.1145/988834

[37] F. Lu, S. Davari, L. Lisle, Y. Li, and D. A. Bowman. Glanceable AR: Evaluating Information Access Methods for Head-Worn Augmented Reality. In *Proceedings - 2020 IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2020*, pp. 930–939, 2020. doi: 10.1109/VR46266.2020.1581100361198

[38] W. Lu, D. Feng, S. Feiner, Q. Zhao, and H. B.-L. Duh. Evaluating subtle cueing in head-worn displays. In *Proceedings of the Second International Symposium of Chinese CHI on - Chinese CHI '14*, pp. 5–10. ACM Press, New York, 2014. doi: 10.1145/2592235.2592237

[39] K. Makita, M. Kanbara, and N. Yokoya. View management of annotations for wearable augmented reality. In *Proceedings - 2009 IEEE International Conference on Multimedia and Expo, ICME 2009*, pp. 982–985, 2009. doi: 10.1109/ICME.2009.5202661

[40] T. Matsumoto, M. Yamazaki, Y. Igarashi, R. Yoshida, and M. Shiraishi. Smart Elevator Hall: Prototype of In-building Guiding Using Interactive Floor Display. In *ISS 2020 - Companion - Proceedings of the 2020 Conference on Interactive Surfaces and Spaces*, pp. 15–18. ACM, New York, NY, USA, 2020. doi: 10.1145/3380867.3426207

[41] T. Matthews. *Designing and Evaluating Glanceable Peripheral Displays*. University of California, Berkeley, 2007.

[42] Microsoft. Microsoft Mixed Reality Comfort. `https://docs.microsoft.com/en-us/windows/mixed-reality/design/comfort`, 2021.

[43] A. Mulloni, H. Seichter, and D. Schmalstieg. Handheld augmented reality indoor navigation with activity-based instructions. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services - MobileHCI '11*, p. 211. ACM Press, New York, USA, 2011. doi: 10.1145/2037373.2037406

[44] J. H. Oh, Y. Jung, Y. Cho, C. Hahm, H. Sin, and J. Lee. Hands-up: motion recognition using kinect and a ceiling to improve the convenience of human life. *Proceedings of CHI 2012 Extended Abstracts*, pp. 1655–1660, 2012.

[45] A. Oliva, M. L. Mack, M. Shrestha, and A. Peeper. Identifying the perceptual dimensions of visual complexity of scenes. In *Proc. of the 26th Annual Meeting of the Cognitive Science Society*, number 26, pp. 1041–1046, 2004.

[46] J. Orlosky, K. Kiyokawa, T. Toyama, and D. Sonntag. Halo content: Context-aware viewspace management for non-invasive augmented reality. In *Proceedings of the 20th International Conference on Intelligent User Interfaces*, IUI '15, p. 369–373. Association for Computing Machinery, New York, NY, USA, 2015. doi: 10.1145/2678025.2701375

[47] M. Otto, E. Lampen, P. Agethen, G. Zachmann, and E. Rukzio. Using large-scale augmented floor surfaces for industrial applications and evaluation on perceived sizes: Personal and ubiquitous computing—theme issue on pervasive displays. *Personal and Ubiquitous Computing*, pp. 1–16, 2020. doi: 10.1007/s00779-020-01433-z

[48] P. Perea, D. Morand, and L. Nigay. Halo3D: A technique for visualizing off-screen points of interest in mobile Augmented Reality. In *IHM 2017 - Actes de la 29ieme Conference Francophone sur Interaction Homme-Machine, Actes*, pp. 43–51. Association for Computing Machinery, Inc, 2017. doi: 10.1145/3132129.3132144

[49] M. G. Petersen, P. G. Krogh, M. Ludvigsen, and A. Lykke-Olesen. Floor interaction hci reaching new ground. In *Conference on Human Factors in Computing Systems - Proceedings*, pp. 1717–1720. ACM, 2005. doi: 10.1145/1056808.1057005

[50] P. Reipschlager, T. Flemisch, and R. Dachselt. Personal Augmented Reality for Information Visualization on Large Interactive Displays. *IEEE Transactions on Visualization and Computer Graphics*, 27(2):1182–1192, 2021. doi: 10.1109/TVCG.2020.3030460

[51] P. Renner and T. Pfeiffer. AR-glasses-based attention guiding for complex environments: Requirements, classification and evaluation. In *ACM International Conference Proceeding Series*, pp. 231–240. ACM, New York, USA, 2020. doi: 10.1145/3389189.3389198

[52] R. Rzayev, S. Hartl, V. Wittmann, V. Schwind, and N. Henze. Effects of position of real-time translation on ar glasses. In *Proceedings of the Conference on Mensch Und Computer*, MuC '20, p. 251–257. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3404983.3405523

[53] M. Satkowski and R. Dachselt. Investigating the Impact of Real-World Environments on the Perception of 2D Visualizations in Augmented Reality. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–15. ACM, New York, NY, USA, 2021. doi: 10.1145/3411764.3445330

[54] S. Schmidt, F. Steinicke, A. Irlitti, and B. H. Thomas. Floor-Projected Guidance Cues for Collaborative Exploration of Spatial Augmented Reality Setups. In *Proceedings of the 2018 ACM International Conference on Interactive Surfaces and Spaces, ISS 2018, Tokyo, Japan, November 25-28, 2018*, pp. 279–289. ACM Press, New York, USA, 2018. doi: 10.1145/3279778.3279806

[55] K. Tanaka, Y. Kishino, M. Miyamae, T. Terada, and S. Nishio. An information layout method for an optical see-through head mounted display focusing on the viewability. In *Proceedings - 7th IEEE International Symposium on Mixed and Augmented Reality 2008, ISMAR 2008*, pp. 139–142, 2008. doi: 10.1109/ISMAR.2008.4637340

[56] T. Thi Minh Tran and C. Parker. Designing exocentric pedestrian navigation for AR head mounted displays. In *Conference on Human Factors in Computing Systems - Proceedings*. Association for Computing Machinery, 2020. doi: 10.1145/3334480.3382868

[57] A. R. Tiley. *The Measure of Man and Woman: Human Factors in Design*. John Wiley & Sons, Inc, revised ed., 2002.

[58] M. Tomitsch. Interactive ceiling - Ambient Information Display for Architectural Environments. p. 178, 2008.

[59] M. Tomitsch and T. Grechenig. Reaching for the Ceiling: Exploring Modes of Interaction. *Adjunct Proceedings of the International Conference on Ubiquitous Computing (Ubicomp'07)*, 2007.

[60] M. Tomitsch, T. Grechenig, A. Vande Moere, and S. Renan. Information sky: Exploring the visualization of information on architectural ceilings. In *Proceedings of the International Conference on Information Visualisation*, pp. 100–105, 2008. doi: 10.1109/IV.2008.81

[61] V. Vechev, A. A. Ünlüer, and A. Dancu. Medium and transition in mobile projected interfaces. In *MobileHCI 2015 - Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct*, pp. 1134–1137. Association for Computing Machinery, Inc, 2015. doi: 10.1145/2786567.2794341

[62] J. Vermeulen, K. Luyten, K. Coninx, N. Marquardt, and J. Bird. Proxemic flow: Dynamic peripheral floor visualizations for revealing and mediating large surface interactions. In *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, vol. 9299, pp. 264–281, 2015. doi: 10.1007/978-3-319-22723-8_22

[63] M. Weiser. The computer for the 21 st century. *ACM SIGMOBILE Mobile Computing and Communications Review*, 3(3):3–11, 1999. doi: 10.1145/329124.329126

[64] W. Willett, Y. Jansen, and P. Dragicevic. Embedded Data Representations. *IEEE Transactions on Visualization and Computer Graphics*, 23(1):461–470, 2017. doi: 10.1109/TVCG.2016.2598608

[65] R. Wimmer, A. Bazo, M. Heckner, and W. Christian. Ceiling Interaction: Properties, Usage Scenarios, and a Prototype. In *Blended Interaction (Workshop) at CHI2013*, 2013.