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The Effect of Layout on Visual Search in Augmented Reality Multi-Window Displays

***Abstract*—Augmented reality (AR) may provide supplementary information to support tasks in the physical world, offering the advantage of displaying multiple windows with high flexibility in interface layout. In AR-physical world mixed scenarios, users often need to locate and retrieve target information from virtual multi-window displays. Understanding how to design effective layouts for these interfaces is critical to enhancing visual search performance, a key element of information retrieval. This study examines the effects of depth separation, information density and curvature of virtual multi-window displays on a conjunctive visual search task in AR. Results indicate that reducing information density and introducing curvature significantly reduced both search time and the time taken to decide that the target was absent (task quit time). Although depth separation did not significantly affect search time, it notably reduced quit time. The number of errors was not significantly influenced by any of the factors. Additionally, users preferred a curved display with lower information density that remained within the device's field of view, and their search time was fastest with this layout. Finally, we noticed variations in layout preference and performance changes among individuals, possibly influenced by differences in search strategies.**

***Index Terms*—Augmented Reality, Visual Search, Multi-Window Displays, Display Layout.**

I. INTRODUCTION

AUGMENTED reality (AR) interfaces have been increasingly used to display information that supports tasks in the physical world. Unlike physical multi-display user interfaces, which usually distribute information in multiple discrete displays [1], AR can create multiple virtual windows of varying presence, size, and arrangement, with minimal cost and effort. These virtual multi-window displays have been tested in various domains, including health care [2], maintenance [3], aviation [4], and everyday applications [5], [6]. When AR displays are used to present supplementary information, users will need to retrieve data from multiple virtual windows. Visual search—i.e., the process of visually locating a target among distractors [7]—is a critical component of this information retrieval process and can be largely influenced by the interface layout. AR's capacity to generate numerous windows in diverse spatial configurations introduces a multitude of display layout possibilities. This raises a variety of questions for display layout design, including those we aim to address in this paper: Should virtual windows be flat or curved? Tightly clustered or more dispersed? Arranged on a single plane or across multiple depths? Remain fully within the field of view (FOV) or extend beyond it?

In this paper, we developed a conjunctive visual search task (i.e., the target and distractors are defined by a combination of multiple features, such as color and shape) using twenty-four virtual windows displayed on a state-of-the-art see-through head-mounted AR headset, which simulates the visual search processes that are common in AR applications with multi-window displays. We conducted an experiment featuring eight AR layouts to investigate the effects of depth separation, information density, and curvature of display on search performance. We also investigated the interaction between the effects of information density and display curvature. The results suggest that introducing depth separation, lowering information density, and creating display curvature all positively impact performance. Participants achieved the fastest search time when using a curved display with lower density that remained within the device's FOV, and this layout was also the most preferred. More detailed findings will be discussed later.

II. RELATED WORK

A. Design of AR Multi-Window Displays

Many previous studies have sought to optimize the design of AR multi-window displays to better support information retrieval. Given AR interfaces overlay virtual content onto the physical environment, it is critical to ensure that virtual worlds are well-aligned with the physical space they are intended to be used in. Various approaches have been proposed to adapt virtual windows to the shapes of physical objects and their spatial arrangements [8]–[10]. Research has also shown that the arrangement of physical objects [11] and their physical and semantic properties [12] can influence user preferences for virtual window placement. Additionally, dynamic layouts that respond to user movement and pose have been shown to aid user interaction with virtual displays [10], [13], [14]. Other work has investigated strategies to reduce interferences between virtual elements [15]–[18] and between virtual windows and physical world interactions [19]. More recent work has explored real-time optimization of mixed-reality layouts that adapt to user context and cognitive load [20].

The research here pertains to studies that examine how different spatial arrangements of virtual windows influence user performance. Imamov et al. [21] investigated the effect of a transparent virtual window's horizontal, vertical, and depth positioning relative to an opaque display on task switching. Their findings suggested that placing the window at eye level or below, and reducing the distance between the interfaces, enhanced both performance and comfort. Perelman et al. [22] found that placing a virtual window in front of the user reduced target acquisition time and head movement compared to positioning it on the right side. Satriadi et al. [23] showed that users preferred multiple virtual windows oriented toward them in a surrounding arrangement while avoiding the overlapping of windows. Similarly, Ens et al. [6] explored multi-window layouts for pointing tasks and recommended a curved design that fits within the user's FOV and minimizes the angular separation between windows.

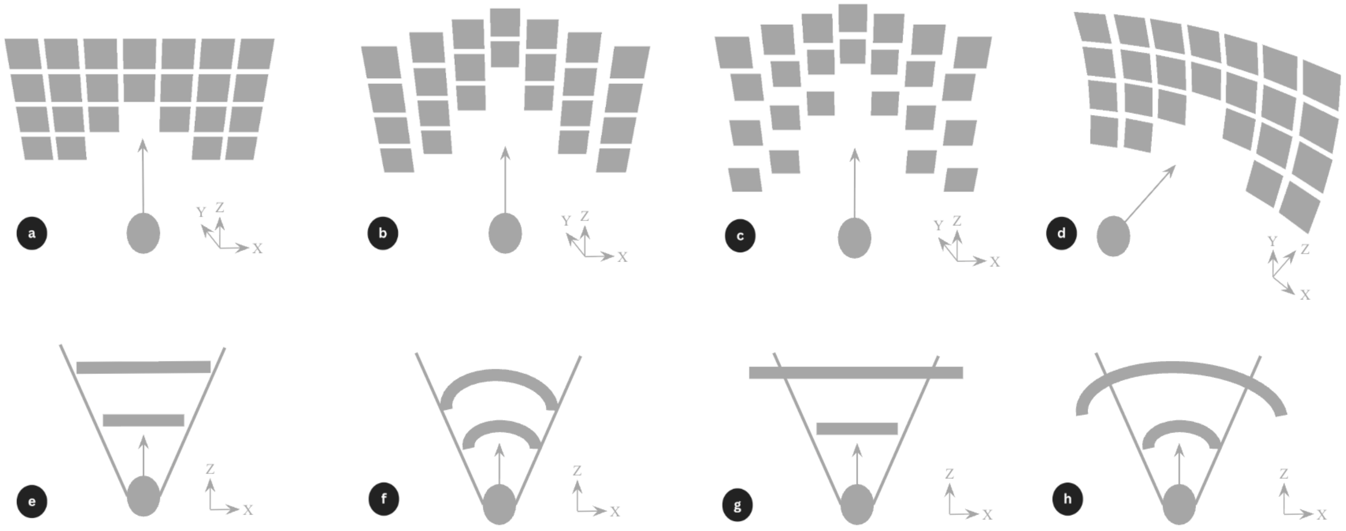

Figure 1: Illustration of the eight AR layout configurations. The visualizations are not to scale and are intended for illustrative purposes only. The circle represents the participant's head position, and the arrow indicates their direction of view. The two straight lines in e, f, g, and h represent the device's horizontal field of view (FOV). a) "Baseline (high-density)" with all windows at the same depth. b) "Column-separated" layout. c) "Column- and row-separated" layout. d) Side view of the "curved high-density" layout. e) Top view of the "medium-density" layout, showing its proximity to the user compared to the "high-density" layout. f) Top view of the "curved medium-density" layout, with reference to the "curved high-density" layout. g) Top view of the "low-density" layout, with reference to the "high-density" layout. h) Top view of the "curved low-density" layout, with reference to the "curved high-density" layout. The x-axis represents the horizontal direction, the y-axis represents the vertical direction, and the z-axis represents the distance from the user.

In this study, we employed a virtual display consisting of twenty-four windows, reflecting the potential future use of AR interfaces, as AR technology allows for the rendering of multiple freely placed virtual windows. Our focus is on how predetermined spatial arrangements of these virtual windows affect visual search performance, a task that is particularly sensitive to the arrangement of visual content. To reflect real-world AR usage scenarios, our layout designs take into account the FOV limitations of current see-through AR headsets and the placement of virtual windows relative to the physical screen displaying the search target cue.

B. Visual Search in Multi-Window Displays

Previous studies have begun exploring the impact of information density and display curvature of virtual windows on visual search performance. Here, we define information density by item sparsity (i.e., the number of items per area) without changing the total item count. Lower information density can reduce visual clutter, which has been shown to enhance search performance [24], [25]. In addition, lower information density may also allow bigger sizes of the search items, a factor known to decrease search time [26]. When the total number of search items stays unchanged, to reduce information density, one can increase display size, which has been shown to increase search time in conjunctive search tasks like the one used in this study [27], [28]. As the display becomes larger, some search items could exceed the device's field of view (FOV). Trepkowski et al. found that increasing FOV may significantly aid visual search [25] and Ren et al. [29] found that a restricted FOV led to slower completion time on a task that included visual search than full FOV. However, in a complex visual search task, sacrificing the ability to keep all content within the restricted FOV of the see-through AR HMD—thus achieving lower information density—may be worthwhile for improving visual search performance. Moreover, adding curvature to displays has been found to enhance performance in text search tasks on physical screens [30], and this benefit may extend to virtual windows in a complex conjunctive search task. While previous work investigated the effect of curvature and information density on visual search performance, no study to our knowledge explored the potential interactions between these two factors.

Depth separation has also been studied as a factor affecting search performance. Prior research suggests that separating items across multiple planes at different depths can improve search accuracy by making it easier for users to fixate on and identify the target after fixation [31]. However, this improvement in accuracy does not necessarily translate to faster search times [31], [32], and may only apply to certain target types (e.g., transparent polygons, X-ray objects, etc.) [31]. In more complex search tasks, depth separation has been shown to increase response time in target-absent trials [32]. Finlayson et al. found that increasing the number of depth planes reduced search efficiency, with items on further planes requiring longer search times [33]. In conjunctive search tasks, Finlayson et al. found no performance benefit from using two depth-separated planes, even when participants were given prior knowledge

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Study	Layout Factors	Task / Environment	Measures	Key Findings
Finlayson et al. (2013)	Depth separation	Letter-based feature and conjunction search on stereoscopic displays	Search time|accuracy	Depth separation improved performance mainly when target depth was known in advance, with limited benefit for conjunction search.
Godwin et al. (2017)	Depth separation	Visual search with transparent and opaque stimuli and X-ray-like images on stereoscopic displays	Search time|accuracy|eye movements	Depth separation improved accuracy primarily for transparent and overlapping stimuli, and altered fixation behavior.
Arefin et al. (2022)	Depth separation	Text visual search with an AR haploscope and a physical monitor	Search time|accuracy|visual fatigue	Increasing focal switching distance reduced search performance and increased visual fatigue. Transient focal blur caused by large depth separation produced further performance decrements.
Kyung & Park (2021)	Curvature|info density	Single-monitor text visual search at a fixed viewing distance	Search time|accuracy|visual fatigue	Moderate curvature reduced search time, improved accuracy, and lowered visual fatigue compared with flat or very large-radius displays. Increasing flat size worsened search time and fatigue, and curvature mitigated those harms.
Shupp et al. (2006)	Curvature|info density	Geospatial search and route tracing on 12 and 24 screen walls	Search time|accuracy|workload	Larger display configurations reduced search time for easier search tasks, and the largest configurations performed best when paired with curvature. Accuracy was similar across configurations and workload was lower for large curved displays.
Tatzgern et al. (2016)	Info density	AR visual search and recall with geo-referenced labels in real scenes	Search time|accuracy	Adaptive info density management reduced search errors and was preferred by the users, but did not consistently reduce search time.
Trepkowski et al. (2019)	FOV|info density	Symbol and text visual search on AR headset and wall displays	Search time|accuracy|workload	Wider FOV and lower info density reduced search time and improved accuracy. A narrower FOV increased the perceived workload.
Wolfe (2012)	Info density	Lab-based symbol and real-world object search	Quit time (threshold)	Higher info density led to a more conservative threshold and thus longer quit time.
Present work	Depth separation|info density|curvature|FOV	Conjunctive visual search across 24 virtual windows in AR	Search time|quit time|accuracy	Results reported in Section V

Table I: Summary of prior visual search studies relevant to the present work and the present work (last row). The table lists the layout factors, task/environment, measures, and key findings from each study.

about the target's depth plane [34]. Having multiple depth planes also requires users to frequently switch their fixations between different depths, a process that has been shown to hinder search performance [21]. In the present work, we aimed to further explore the effect of depth separation in visual search within a complex task involving high visual clutter generated by multiple virtual windows. Our motivation was to investigate whether reducing visual clutter by positioning virtual windows at different depth planes could outweigh the additional search effort required.

III. PRESENT WORK

Table I summarizes similar prior studies that have examined visual search performance with some of the layout factors and dependent measures considered in this study. Compared to previous work exploring depth separation, our study differs in both motivation and implementation. Earlier studies used depth separation to reduce visual clutter between overlapping items along the same x–y plane [31], [34] or between two side-by-side screens [35]–[38], whereas our design employed a relatively small depth separation to reduce spatial clutter among a large number of non-overlapping virtual windows. In prior research, the level of separation was typically controlled by the distance between depth planes, whereas our study introduced both column- and row-based depth separation between windows to simulate a structured, three-dimensional layout. Building on studies that examined display curvature and information density, we further investigated the trade-off between reducing information density and extending portions of the display beyond the FOV, a foundational design consideration for current AR headsets. We also examined whether introducing curvature could mitigate the costs of having parts of the display extend beyond the FOV. Our task design was also unique from prior work, employing a challenging conjunctive visual search task with three target-defining variables across multiple virtual windows, an arrangement that reflects realistic AR usage contexts. Finally, in addition to the commonly measured search time and accuracy, we incorporated the dependent measure of 'quit time' to quantify the user's decision threshold for ending a search. While previous studies have examined how quit time is affected by factors such as distractor properties, target prevalence, and information density [39]–[41], few have explored how curvature or depth separation influence this measure. Addressing this gap represents an important contribution of the present work.

Motivated by the unique flexibility of AR to manipulate

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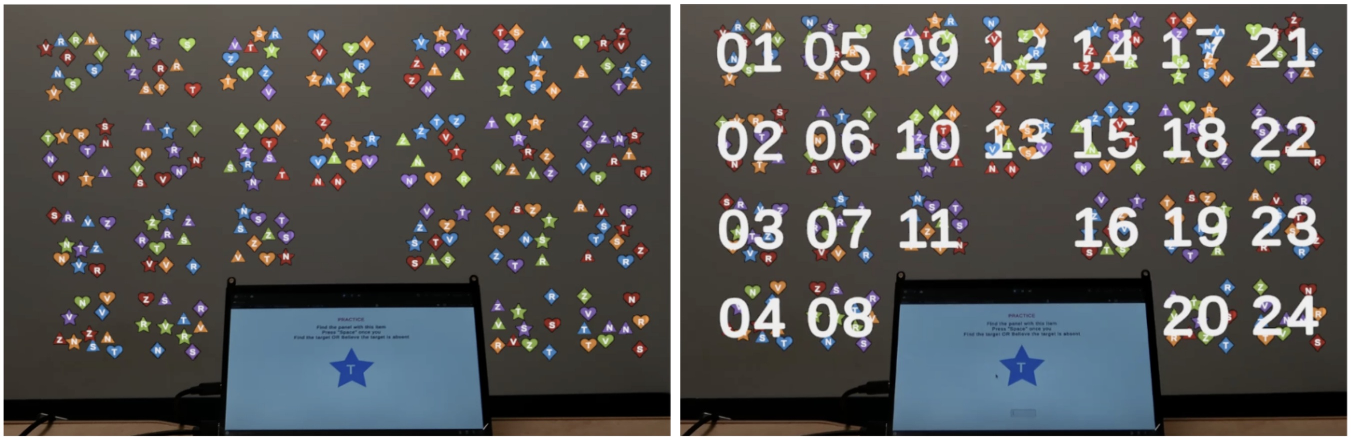

Figure 2: Left: The search panel displayed to the user at the start of each trial. Right: The window indices overlaid on the virtual windows after the user presses the space key to indicate they have located the target.

virtual window depth, curvature, and information density, we designed a controlled study to examine how these layout factors affect visual search performance while accounting for the FOV constraints of current AR headsets. Specifically, we investigated their effects on search time, quit time, and accuracy in a stationary AR condition that emulates workstation scenarios, where virtual displays serve as low-cost, adjustable, and supportive information panels. The goal of this work is to provide foundational design insights for AR applications that employ multi-window layouts, which may also generalize to other multi-display user interfaces with comparable spatial configurations. Our research questions were as follows:

1. How does depth separation between virtual windows affect search performance?
2. How do information density, curvature of the virtual multi-window display, and their interaction affect search performance?
3. How can we understand the effect of the aforementioned factors based on user preferences and the self-described search strategies?

IV. EXPERIMENT

A. Apparatus

The virtual windows were displayed on a Magic Leap 2 see-through augmented reality headset, which has a resolution of 1440 × 1760 pixels per eye and a diagonal FOV of 70 degrees. The physical display used to present the search target was a 10.1-inch monitor with a resolution of 1024 × 600 pixels, connected to a Macbook laptop with the M1 Pro chip. The experiment was developed using the Unity game engine, and participants interacted with the program via a full-sized Bluetooth keyboard. Both the physical display and keyboard were placed on a table, with participants seated in a chair during the experiment. The positions of the chair and table remained fixed throughout the study. The physical display remained at 1 meter from participants in all conditions.

B. Participants

Twenty university students (12 males, 8 females, $M = 23.5$, $SD = 3.2$) were recruited for this study. All participants had normal or corrected-to-normal vision and normal color vision. The study was approved by the university's Institutional Review Board. Standard IRB protocols were followed to ensure informed consent, participant anonymity, and data security throughout the experiment. The participants were compensated with gift cards for their time.

C. Task

We developed a conjunctive search task that required the participants to read search cues from a physical display, identify the virtual window containing the target, and input the search results to the physical display. This procedure simulates a real-world scenario where users retrieve information required by their physical task from multiple virtual windows in AR. The target item and distractors could share the same color, shape, or text. In each search trial, participants first viewed the target item on the physical display (see Figure 2 left), then located the virtual window containing the target among twenty-four equally sized virtual windows. Upon identifying the target, they pressed the space key on a keyboard, at which point response time was recorded. Following the key press, a two-digit number representing the index of each virtual window (ranging from 01 to 24) appeared on the windows (see Figure 2 right). Participants then typed the index of the identified window into the input field displayed on the physical screen. If participants concluded that the target was absent after a careful search, they pressed the space key and entered "00". There was no time limit for the search, but participants were instructed to prioritize accuracy while aiming to perform the search as quickly as possible. All virtual windows were world-fixed, remaining anchored to the same positions in the environment rather than following the user's viewpoint. Therefore, participants could move their heads to focus on different windows for all conditions.

Each of the 24 virtual windows contained 10 randomly positioned items, meaning a total of 240 items were displayed in each search trial. Each item could be one of five colors (red, orange, green, blue, or purple), one of four shapes (heart, star, diamond, or triangle), and one of six capitalized letters (“R”, “V”, “N”, “T”, “S”, “Z”). These attributes generated 120 unique combinations. In target-present trials, one combination was selected as the unique target item, while the remaining 119 combinations appeared twice, generating 239 items, with one additional item using a randomly selected non-target combination. In target-absent trials, where the target item was not present in the virtual windows, the target was replaced by an item using another one of the 119 non-target combinations. Within each virtual window, no more than three occurrences of the same color, shape, or text were allowed. To arrange these windows symmetrically within the headset's field of view while maintaining comfortable viewing angles, we adopted the current seven-column layout shown in Figure 2. A pilot test (N=5) was conducted before the experiment to calibrate the task's difficulty and ensure no combination was disproportionately difficult or easy to locate, and that the target was clearly visible across all layout conditions.

D. Experimental Design

Each participant performed the task under eight different conditions, each characterized by distinct virtual window layouts representing various levels of depth separation, information density, and curvature of virtual windows. The eight layouts were selected to balance experimental completeness and feasibility within a within-subject design. Depth separation was explored specifically under high-density layouts, where its potential benefits in mitigating visual clutter would be most relevant. In contrast, lower information density and display curvature were examined as alternative strategies for reducing clutter without depth layering. The conditions are listed below:

- **Baseline (high-density with no depth separation)** (Figure 1a): Virtual windows were positioned at the same distance on the z-axis as the physical display (1 meter), with all windows parallel to the plane of the physical display.
- **Column-separated** (Figure 1b): Compared to the no-separation baseline, every column of virtual windows was staggered by 6 cm along the z-axis from its neighboring columns. To prevent excessive distance from the user, symmetry was maintained using the middle column. Labeling the columns from left to right as 1 through 7, columns 1 and 7, 2 and 6, and 3 and 5 shared the same depth, with column 4 furthest from the user and columns 1 and 7 closest. The average z-distance across all columns matched the z-distance in the “no-separation baseline” condition.
- **Column- and row-separated** (Figure 1c): In addition to depth separation between columns, every row of virtual windows was also staggered by 6 cm on the z-axis from its neighboring rows. A similar depth manipulation was applied to the rows. Labeling the rows from top to bottom as 1 through 4, row 2 was furthest from the user and row 4 was closest, and rows 1 and 3 shared the same depth. As a result, each window's top, bottom, left, and right neighbors were at different depths than it. The average z-distance across all windows remained equivalent to the “no-separation baseline” condition.
- **Curved high-density** (Figure 1d): This condition introduced a curved display layout, applying x- and y-rotations to the virtual windows in the “high-density baseline” based on user feedback from a pilot test, such that all windows approximately faced the user's head position. X-axis rotations for the top to bottom rows were -10°, 0°, 10°, and 20°, while y-axis rotations for the left to right columns were -18°, -12°, -6°, 0°, 6°, 12°, and 18°.
- **Medium-density** (Figure 1e): Compared to the “high-density baseline”, the virtual windows were positioned 4m farther from the user so that they appeared about 1.5 times larger visually while remaining within the headset's field of view. This visual scaling reduced information density without exceeding the FOV.
- **Curved medium-density** (Figure 1f): In this condition, x and y rotations were applied to the virtual windows in the “medium-density” condition. Pilot feedback suggested that increasing y-axis rotation would visually align the curvature more closely with the high-density baseline. Consequently, y-axis rotations for the left to right columns were adjusted to -24°, -16°, -8°, 0°, 8°, 16°, and 24°. X-axis rotations remained the same as in the “high-density” condition.
- **Low-density** (Figure 1g): In this condition, the height and width of the virtual windows were further increased by 1.5 times compared to the “medium-density” condition. The windows exceeded the headset's horizontal FOV, requiring participants to move their heads during the search. This was intentionally done to test whether decreasing density was beneficial to counter the added effort resulting from head movement. The medium-density layout, in contrast, provided full visibility of the display to provide a control condition for comparison.
- **Curved low-density** (Figure 1h): In this condition, x and y rotations were applied to the virtual windows in the “low-density” condition. Based on pilot feedback, y-axis rotation was further increased, with the left to right columns adjusted to -30°, -20°, -10°, 0°, 10°, 20°, and 30°. X-axis rotations remained the same as in the “high-density” condition.

Each condition consisted of 24 target-present trials presented in random order, with the target appearing once in each of the 24 virtual windows. Additionally, three target-absent trials were randomly integrated into the sequence, and three practice trials were provided at the beginning of each condition. Participants were unaware of the total number of target-present or target-absent trials. The order of conditions was randomized for each participant. For the target items in the 24 target-present trials, each of the five colors appeared no more than five times, each of the four shapes no more than six times, and each of the six text letters no more than four times.

E. *Statistical Analysis*

Linear mixed models [42] were used to assess the effects of depth separation, display curvature, and information density on each of our metrics. Two separate analyses were conducted to tackle our research questions. The first analysis examined the influence of depth using three levels of depth configurations: no depth separation, column-separated, and column- and row-separated. For this, a one-way linear mixed model with three levels was applied to each metric. The second analysis explored the effects of curvature and information density across various conditions: high-density, medium-density, low-density, curved high-density, curved medium-density, and curved low-density, resulting in a 2 × 3 factorial design for the linear mixed models applied to each metric.

Each model was fitted using stepwise forward selection with full maximum likelihood estimation. Initially, the model included random intercepts for participants, then fixed effects for the predictor variables and their interactions were incrementally added. The significance of each factor was assessed using likelihood ratio tests, with p-values adjusted using Holm's step-down method to maintain a familywise error rate of 0.05. Significant effects were further examined using Bonferroni-corrected paired t-tests. Residuals were examined using QQ plots for normality and residuals versus fitted plots for heteroskedasticity. No data transformations were performed. All tests were conducted at a significance level of α= 0.05, and estimated marginal means were used for bar plot visualizations. The statistical analysis was carried out using R [43].

For each layout, the study considered three dependent measures that reflect search performance: search time, quit time, and number of errors. Both search time and quit time were recorded from the onset when the visual stimuli were presented until they pressed the space key. If the participant entered "00," indicating they could not locate the target, the time would be logged as quit time, regardless of whether the target was present or absent. Quit time reflects the duration a user takes to decide to quit after conducting an exhaustive search. Search time was recorded only when the participant's response correctly matched the index of the window containing the target item. The number of errors represented how often participants made incorrect selections during both target-present and target-absent trials. Additionally, qualitative data were collected in a post-study survey, including each participant's ranking of layout preferences and open-ended questions inquiring about their search strategies.

V. RESULTS

A. *Effect of Depth*

Depth did not influence search time ($\chi^2(2)$ = 5.04, p = .160) and number of errors ($\chi^2(2)$ = .609, p = .737). Descriptive statistics indicated that the mean search times of no-separation, column-separated, and column- and row-separated layouts were 11.6 s (SD = 7.72), 10.94 s (SD = 7.17), and 10.62 s (SD = 6.36) respectively. Although the main effect of depth on search time was not significant, there was substantial variability across individuals. The spaghetti plot in Figure 3 illustrates how the changes in participants' search times varied with increasing levels of depth separation (lowest to highest): no depth separation, column- separation, and column- and row-separation. The mean search times of four participants consistently increased as depth increased while nine participants consistently decreased. Four participants' search times increased with column-separation, but decreased with column- and row-separation; three participants decreased with column-separation, but increased with column- and row-separation.

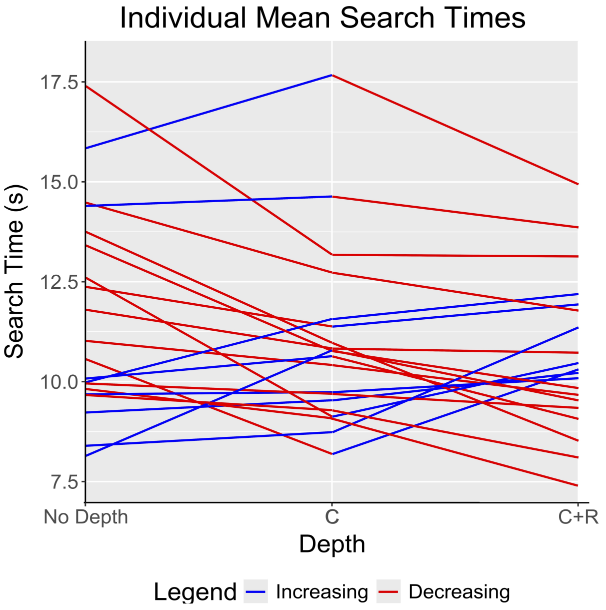

Figure 3: Spaghetti plots illustrating individual participants' search times as a function of depth (No Depth, C=Column-separated, C+R=Column- and row-separated). Each line represents a participant, with depth conditions on the x-axis and time on the y-axis. Blue lines show increasing search times between the two connected depths; red lines show decreasing search times.

Depth had a significant main effect on quit time ($\chi^2(2)$ = 37.29, p < .001), where the no-separation layout had longer task quit times than the column-separated (mean difference = 6.10 s, t(195) = 4.01, p < .001) and column- and row-separated layouts (mean difference = 9.55 s, t(195) = 6.28, p < .001). The bar plots for search time, quit time, and number of errors are shown in Figure 4.

B. *Effect of information density and curvature*

Information density significantly influenced search time ($\chi^2(2)$ = 15.51, p < .001), where the high information density layouts had longer search times than the medium (mean difference = 1.65 s, t(2810) = 5.57, p < .001) and low information density ones (mean difference = 1.60 s, t(2810) = 5.39, p < .001). In addition, information density significantly affected task quit times ($\chi^2(2)$ = 12.61, p = .001), where the high information density layouts had longer quit times than

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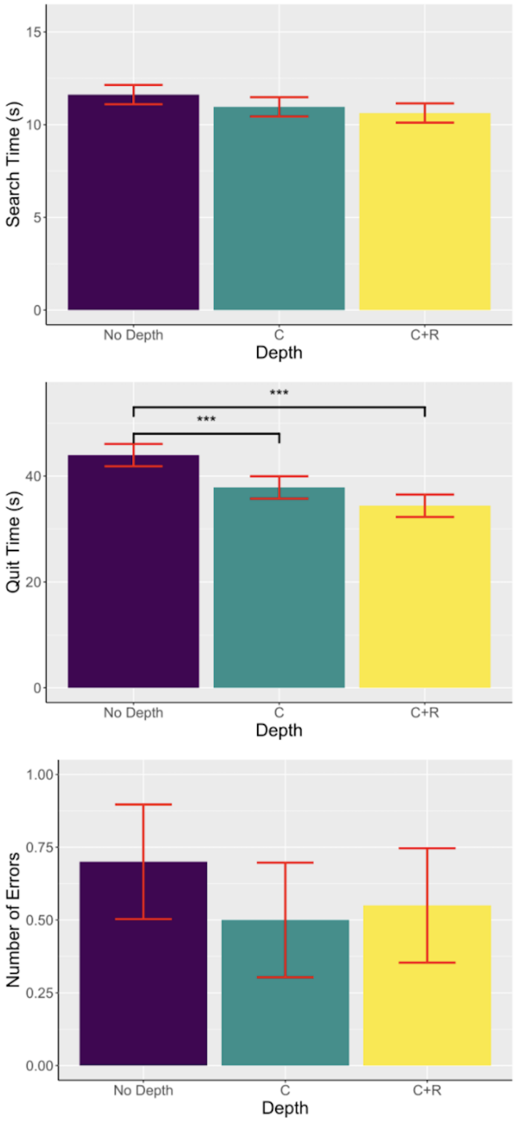

Figure 4: Bar plots depicting the mean values and standard errors of search time (top), quit time (middle) and number of errors (bottom) as a function of depth separation (No Depth, C=Column-separated, C+R=Column- and row-separated). *** indicates the comparison was significant at the $p < .001$ level, otherwise the comparison was insignificant.

the medium (mean difference $= 4.31$ s, $t(397) = 3.67$, $p < .001$) and low-density ones (mean difference $= 7.47$ s, $t(397) = 6.74$, $p < .001$). The medium-density layout also had longer quit times than the low-density one (mean difference $= 3.34$ s, $t(397) = 2.95$, $p = .009$).

Display curvature also had a significant main effect on search and quit times, where the curved layouts had faster search times ($\chi^2(1) = 15.51$, mean difference $= .962$ s, $t(2810) = 3.97$, $p < .001$), and quit times ($\chi^2(1) = 12.61$, mean difference $= 3.27$ s, $t(397) = 3.57$, $p = .001$). The significant information density × curvature interaction effect on quit time ($\chi^2(2)= 25.32$, $p < .001$) showed that the difference between information density conditions was only significant when the layouts were uncurved. The difference between high and medium information density layouts was significant when the layouts were uncurved (mean difference $= 9.25$ s, $t(397) = 5.94$, $p < .001$) but not uncurved (mean difference $= .986$ s, $t(397) = .321$, $p = 1.00$). Neither information density ($\chi^2(2) = 2.07$, $p = .150$) nor curvature ($\chi^2(1) = 3.88$, $p = .143$) had a significant main effect on the number of errors. The bar plots showing the effects of information density with and without display curvature are shown in Figure 5. Finally, we generated a spaghetti plot, shown in Figure 6, to visually examine how individual differences might contribute to the non-significant results observed in quit time for curved layouts. As information density decreased from high to medium to low, the changes in individual mean quit times varied: the mean quit time of two participants consistently increased as information density decreased while five participants consistently decreased. Ten participants' quit time increased with medium-density, but decreased with low-density; three participants decreased with medium-density, but increased with low-density.

C. *Qualitative Data Analysis*

We collected participants' rankings of their preferences for the eight layouts and then aggregated these rankings to determine overall preferences. The layouts, ranked from most to least preferred, were as follows: curved medium-density, medium-density, baseline (high-density with no depth separation), curved high-density/ curved low-density (equal rank), column-separated, low-density, column- and row-separated. Overall, 35% of participants ranked the curved medium-density condition as the most favored display, whereas 30% ranked the column- and row-separated condition as the least favored. Within the medium-density layouts, 60% of participants preferred the curved condition over the uncurved one, and within the low- and high-density layouts, 55% also preferred the curved condition over the uncurved one.

Participants were asked to describe their general search strategies across all conditions. Six of the twenty participants reported initially conducting a quick scan of the display before engaging in a more thorough search. Eight participants indicated that they prioritized color over shape and letter during the search, while three mentioned focusing on items with the same combination of color and shape as the target. For most, the letter feature was the least prioritized. Additionally, seven participants described using a zig-zag search pattern, either moving row by row or column by column.

When asked about specific strategies for different layouts, nine participants stated they applied the same approach across all conditions. Four participants mentioned scanning column by column only in conditions where columns were separated by depth. Participants also made various comments on how their strategies evolved in medium and low information density conditions. Some noted, "I prefer moving my head while searching," "I tend to look through quickly," "I would randomly skim through first," and "I would remember all features rather than focusing on one initially." Two participants mentioned scanning thoroughly on one side (left or right)

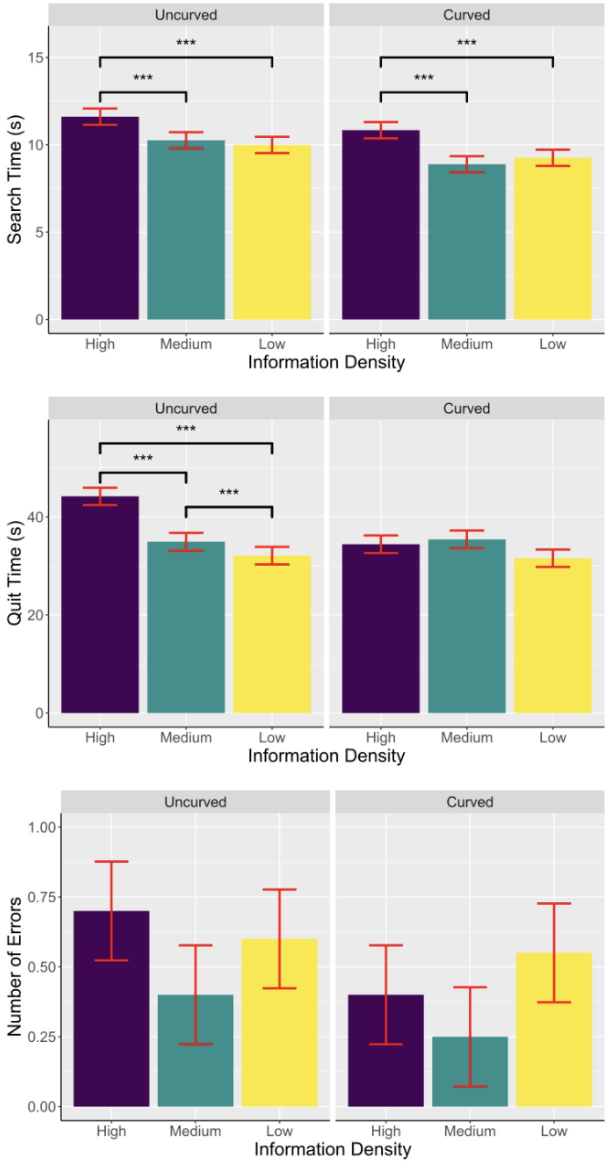

Figure 5: Bar plots depicting the mean values and standard errors of search time (top), quit time (middle) and number of errors (bottom) as a function of information density and curvature. *** indicates the comparison was significant at the $p < .001$ level, otherwise the comparison was insignificant.

before moving to the other. In the lowest information density condition, where some items were outside the FOV, one participant found it helpful for “minimizing the information at any given time,” while another noted that it made quick scanning “less effective because I couldn’t see the entire display.”

VI. DISCUSSION

A. R.Q.1: “How does depth separation between virtual windows affect search performance?”

The results indicate that introducing depth separation did not significantly affect search time or the number of errors. Increasing the level of separation by creating more depth planes also had no significant effect on search performance. In contrast to some previous studies, which found that introducing additional depth planes could hinder performance [33], our results show that introducing and increasing depth separation did not negatively impact performance. This could suggest that the reduced visual clutter offsets the additional search effort caused by multiple depth planes. However, it is important to highlight that the crossing of the lines with positive and negative slopes in Figure 3 reveals substantial individual differences in the direction of the effect of depth separation on search time, suggesting that the variation in individual search behaviors might have contributed to the lack of statistically significant results. Additionally, the relatively small distance between the depth planes in this study might have reduced the effort associated with depth separation compared to previous research.

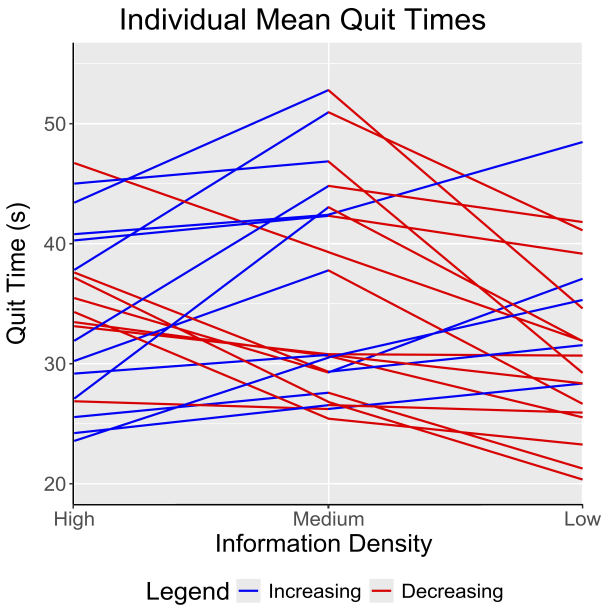

Figure 6: Spaghetti plots illustrating individual participants’ quit times as a function of information density for the curved conditions in which no significant results were observed. Each line represents a participant, with information density conditions on the x-axis and time on the y-axis. Blue lines show increasing quit times between the two connected conditions; red lines show decreasing quit times.

Furthermore, compared to the no-separation condition, quit time was significantly reduced in the conditions with depth separation. This differs from findings in previous research [32], possibly due to different task and study designs. Depth separation could have guided users to search through depth planes sequentially, as suggested by their self-reported search strategies. This could have influenced the dwelling, skipping, and revisiting of distractors, factors that previous research has shown to impact quit time [44]. Further confirmation of this hypothesis will require analysis of future eye-tracking data.

If examining the individual lines in Figure 3 more closely, we can observe some V-shaped patterns, with the “V” pointing in both upward and downward directions. This suggests that for certain participants, search time decreased when only columns were separated but increased when both columns and rows were separated, or vice versa. Meanwhile, many lines show continuous improvement or decline in performance as the level of separation increased. These observations further highlight the individual differences in how depth separation affects performance.

B. R.Q.2: "How do information density, curvature of the virtual multi-window display, and their interaction affect search performance?"

The results show that reducing information density and creating display curvature significantly reduced both search time and quit time, without significantly affecting the number of errors. This is consistent with earlier results showing that moderate curvature improves search efficiency and the user's comfort [45], [46] and that lower information density facilitates visual search by reducing clutter [24], [25]. Search time was significantly lower in the medium and low information density conditions compared to the high-density baseline, regardless of whether the display was curved. However, the insignificant difference between medium and low information density conditions indicates that the positive effect of having lower density becomes incremental beyond a certain point, potentially when the part of the windows were outside of the FOV. This pattern aligns with findings by Trepkowski et al. (2019), who reported that performance improvements from reduced information density diminish once the visible area of the AR display is exceeded.

Quit time significantly decreased as the information density reduced, although this effect was only observed in conditions without display curvature. In addition to the notably lower mean quit time observed in the curved high-density condition compared to the uncurved high-density condition, the lack of significant results in quit time differences between curved conditions could be caused by the individual differences shown in Figure 6, which shared similar patterns as observed in search time of different depth separation levels. The statistical test results indicated that introducing curvature to the virtual display is a promising design strategy to enhance visual search, as it improves both search and quit times without impacting the number of errors, even with small curvature. For applications prioritizing efficiency and restricted display size, creating display curvature could be a viable approach to improve search performance. A curved display could reduce the variation in the distance between the user and each window by making the layout more radial. This more consistent proximity could help explain the performance improvement observed with the curved display.

Although extending the display beyond the FOV could require more effort in searching, it did not significantly affect search time or errors. It was also surprising to find that quit time was lowest in the low-density condition, despite the search items extending beyond the FOV. This suggests that the potential additional search effort required for eye and head movement due to the larger screen size, along with the drawback of not seeing all items simultaneously, might be offset by the benefits of larger search items and reduced visual clutter.

C. R.Q.3: "How can we understand the effect of the aforementioned factors from user preferences and the self-described search strategies?"

We found that the most preferred layout was "curved medium-density," which also resulted in the lowest average search time. Medium-density was preferred over both high and low-density layouts, suggesting that users favor sparser search items, while having everything presented within the device's FOV. There were slightly more participants who preferred curved layouts over uncurved ones across all low-, medium-, and high-density conditions. More participants favored the no-separation baseline over the depth-separated layouts, although eight of the twenty participants still preferred at least one of the depth-separated layouts compared to the non-separated baseline.

The self-reported search strategies indicated that depth separation influenced how users approached the task by encouraging them to move sequentially between depth planes. Similar sequential search behaviors have been observed in stereoscopic displays where depth segmentation guided fixation patterns [31], [34]. Lower information density had varying effects on users: some favored a more random skimming approach, potentially due to the larger and sparser items, while others focused on minimizing switches between display regions. Interestingly, some participants liked having parts of the display outside the FOV, as it reduced distractions during searching, while others found this layout less effective for quick scanning. This was in line with the findings of Trepkowski et al. [25], who reported that having fewer distractors within the field of view was sometimes preferred because it reduced visual clutter and helped users focus on the current region. However, the increased need for scanning could ultimately decrease overall performance and lead to higher subjective workload.

VII. LIMITATION AND FUTURE WORK

In the next phase, we plan to collect and analyze participants' eye and head movement data to further understand the differences in search strategies and behaviors across the conditions, which could provide insights into the performance variations. In the previous sections, we have discussed how manipulating the three design factors may result in different performance outcomes between participants. The eye and head movement data could also help understand these individual differences. Additionally, we plan to investigate whether search times and the number of errors vary across specific columns, rows, or regions of the display, and how such variations are influenced by different layout designs, if present.

A more detailed analysis of the qualitative data is also valuable. Future steps could include examining whether a user's preferences align with their performance across different layouts. Additionally, eye and head movement data could provide more insights into user preferences and help verify the accuracy of self-reported strategies. For instance, while

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most participants stated that they used the same strategy across layouts, there may be subtle changes in behavior they were unaware of.

In this study, we aimed to provide foundational design insights for visual search in AR multi-display user interfaces with flexible layouts. To better reflect real-world uses of AR, future work could explore more dynamic scenarios that involve user or display movement, deeper integration of information from both virtual and physical environments during the search process, and the assignment of different windows to specific functions to introduce contextual priming in visual search.

For this line of work, we controlled the characteristics of the search items by using simple combinations of color, shape, and text. Future research could explore more complex search items like real images or 3D objects, which may further impact search performance. Moreover, the untimed nature of this study made the user unlikely to make errors, and the task in future studies can be more error-prone. Another potential direction is expanding the search region to require greater head or even body movement. In such cases, the layout of physical environments and the placement of physical objects could be integrated into the design of multi-window virtual displays. Based on findings in previous literature, we hypothesize that display layouts that minimize visual noise from the physical environment may lead to better search performance. Future work could further disentangle the effects of column compared to row separation to determine whether the observed benefits of depth layering depend on the direction of separation.

VIII. CONCLUSION

In this study, we investigated the effects of depth separation, information density, and display curvature in an AR multi-window interface on conjunctive visual search performance. We measured participants' search time, quit time, and accuracy. Our findings revealed that depth separation between windows decreased quit time without increasing errors. Additionally, reducing information density and incorporating display curvature led to faster search and quit times. Expanding the display beyond the device's FOV neither significantly improved nor worsened search time or accuracy. These results suggest that designers should consider using curved, larger virtual multi-window displays, provided they remain within the FOV, which is also most preferred among participants. We also observed notable individual differences in layout preferences and performance changes, potentially driven by varied search strategies.

REFERENCES

[1] U. Rashid, M. A. Nacenta, and A. Quigley, "Factors influencing visual attention switch in multi-display user interfaces: A survey," in *Proceedings of the 2012 international symposium on pervasive displays*, 2012, pp. 1–6.

[2] L. Ma, T. Huang, J. Wang, and H. Liao, "Visualization, registration and tracking techniques for augmented reality guided surgery: a review," *Physics in Medicine & Biology*, vol. 68, no. 4, p. 04TR02, 2023.

[3] D. Ariansyah, J. A. Erkoyuncu, I. Eimontaite, T. Johnson, A.-M. Oostveen, S. Fletcher, and S. Sharples, "A head mounted augmented reality design practice for maintenance assembly: Toward meeting perceptual and cognitive needs of ar users," *Applied Ergonomics*, vol. 98, p. 103597, 2022.

[4] J. Tan, H. Ye, C. Xu, H. He, and X. Liao, "Skyroadar: An augmented reality system for uavs low-altitude public air route visualization," *Drones*, vol. 7, no. 9, p. 587, 2023.

[5] F. Lu and D. A. Bowman, "Evaluating the potential of glanceable ar interfaces for authentic everyday uses," in *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*. IEEE, 2021, pp. 768–777.

[6] B. M. Ens, R. Finnegan, and P. P. Irani, "The personal cockpit: a spatial interface for effective task switching on head-worn displays," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2014, pp. 3171–3180.

[7] J. M. Wolfe, "Visual search: How do we find what we are looking for?" *Annual review of vision science*, vol. 6, no. 1, pp. 539–562, 2020.

[8] V. Y. Han, H. Cho, K. Maeda, A. Ion, and D. Lindlbauer, "Blendmr: A computational method to create ambient mixed reality interfaces," *Proceedings of the ACM on Human-Computer Interaction*, vol. 7, no. ISS, pp. 217–241, 2023.

[9] Y. Cheng, Y. Yan, X. Yi, Y. Shi, and D. Lindlbauer, "Semanticadapt: Optimization-based adaptation of mixed reality layouts leveraging virtual-physical semantic connections," in *The 34th Annual ACM Symposium on User Interface Software and Technology*, 2021, pp. 282–297.

[10] W. S. Lages and D. A. Bowman, "Walking with adaptive augmented reality workspaces: design and usage patterns," in *Proceedings of the 24th International Conference on Intelligent User Interfaces*, 2019, pp. 356–366.

[11] W. Luo, A. Lehmann, H. Widengren, and R. Dachselt, "Where should we put it? layout and placement strategies of documents in augmented reality for collaborative sensemaking," in *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, 2022, pp. 1–16.

[12] M. O. Ellenberg, M. Satkowski, W. Luo, and R. Dachselt, "Spatiality and semantics-towards understanding content placement in mixed reality," in *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*, 2023, pp. 1–8.

[13] W. Lages and D. Bowman, "Adjustable adaptation for spatial augmented reality workspaces," in *Symposium on spatial user interaction*, 2019, pp. 1–2.

[14] M. Mcgill, A. Kehoe, E. Freeman, and S. Brewster, "Expanding the bounds of seated virtual workspaces," *ACM Transactions on Computer-Human Interaction (TOCHI)*, vol. 27, no. 3, pp. 1–40, 2020.

[15] R. Grasset, T. Langlotz, D. Kalkofen, M. Tatzgern, and D. Schmalstieg, "Image-driven view management for augmented reality browsers," in *2012 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, 2012, pp. 177–186.

[16] 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*, 2001, pp. 101–110.

[17] S. D. Peterson, M. Axholt, M. Cooper, and S. R. Ellis, "Visual clutter management in augmented reality: Effects of three label separation methods on spatial judgments," in *2009 IEEE Symposium on 3D User Interfaces*. IEEE, 2009, pp. 111–118.

[18] 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, 2003. Proceedings.* Tokyo, Japan: IEEE Comput. Soc, 2003, pp. 66–75. [Online]. Available: http://ieeexplore.ieee.org/document/1240689/

[19] 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*, 2015, pp. 369–373.

[20] D. Lindlbauer, A. M. Feit, and O. Hilliges, "Context-Aware Online Adaptation of Mixed Reality Interfaces," in *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. New Orleans LA USA: ACM, Oct. 2019, pp. 147–160. [Online]. Available: https://dl.acm.org/doi/10.1145/3332165.3347945

[21] 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)*. IEEE, 2020, pp. 851–858.

[22] G. Perelman, E. Dubois, A. Probst, and M. Serrano, "Visual transitions around tabletops in mixed reality: study on a visual acquisition task between vertical virtual displays and horizontal tabletops," *Proceedings of the ACM on Human-Computer Interaction*, vol. 6, no. ISS, pp. 660–679, 2022.

[23] K. A. Satriadi, B. Ens, M. Cordeil, T. Czauderna, and B. Jenny, "Maps around me: 3d multiview layouts in immersive spaces," *Proceedings of the ACM on Human-Computer Interaction*, vol. 4, no. ISS, pp. 1–20, 2020.

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[24] M. Tatzgern, V. Orso, D. Kalkofen, G. Jacucci, L. Gamberini, and D. Schmalstieg, “Adaptive information density for augmented reality displays,” in *2016 IEEE Virtual Reality (VR)*. IEEE, 2016, pp. 83–92.

[25] C. Trepkowski, D. Eibich, J. Maiero, A. Marquardt, E. Kruijff, and S. Feiner, “The effect of narrow field of view and information density on visual search performance in augmented reality,” in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 2019, pp. 575–584.

[26] C. C. Gramazio, K. B. Schloss, and D. H. Laidlaw, “The relation between visualization size, grouping, and user performance,” *IEEE transactions on visualization and computer graphics*, vol. 20, no. 12, pp. 1953–1962, 2014.

[27] J. Marsh, M. E. Miller, E. E. Geiselman, and P. Havig, “Display size and distractor complexity effects on visual search,” *Displays*, vol. 66, p. 101988, 2021.

[28] I.-P. Chen, C.-N. Liao, and S.-H. Yeh, “Effect of display size on visual attention,” *Perceptual and motor skills*, vol. 112, no. 3, pp. 959–974, 2011.

[29] D. Ren, T. Goldschwendt, Y. Chang, and T. Höllerer, “Evaluating wide-field-of-view augmented reality with mixed reality simulation,” in *2016 IEEE Virtual Reality (VR)*. IEEE, 2016, pp. 93–102.

[30] S. Park, D. Choi, J. Yi, S. Lee, J. E. Lee, B. Choi, S. Lee, and G. Kyung, “Effects of display curvature, display zone, and task duration on legibility and visual fatigue during visual search task,” *Applied ergonomics*, vol. 60, pp. 183–193, 2017.

[31] H. J. Godwin, T. Menneer, S. P. Liversedge, K. R. Cave, N. S. Holliman, and N. Donnelly, “Adding depth to overlapping displays can improve visual search performance.” *Journal of experimental psychology: human perception and performance*, vol. 43, no. 8, p. 1532, 2017.

[32] ——, “Experience with searching in displays containing depth improves search performance by training participants to search more exhaustively,” *Acta Psychologica*, vol. 210, p. 103173, 2020.

[33] N. J. Finlayson and P. M. Grove, “Visual search is influenced by 3d spatial layout,” *Attention, Perception, & Psychophysics*, vol. 77, no. 7, pp. 2322–2330, 2015.

[34] N. J. Finlayson, R. W. Remington, J. D. Retell, and P. M. Grove, “Segmentation by depth does not always facilitate visual search,” *Journal of Vision*, vol. 13, no. 8, pp. 11–11, 2013.

[35] M. S. Arefin, N. Phillips, A. Plopski, J. L. Gabbard, and J. E. Swan, “The Effect of Context Switching, Focal Switching Distance, Binocular and Monocular Viewing, and Transient Focal Blur on Human Performance in Optical See-Through Augmented Reality,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 28, no. 5, pp. 2014–2025, May 2022. [Online]. Available: https://ieeexplore.ieee.org/document/9714039/

[36] J. L. Gabbard, D. G. Mehra, and J. E. Swan, “Effects of AR Display Context Switching and Focal Distance Switching on Human Performance,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 25, no. 6, pp. 2228–2241, Jun. 2019. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/8353823

[37] A. Eiberger, P. O. Kristensson, S. Mayr, M. Kranz, and J. Grubert, “Effects of Depth Layer Switching between an Optical See-Through Head-Mounted Display and a Body-Proximate Display,” in *Symposium on Spatial User Interaction*, ser. SUI ’19. New York, NY, USA: Association for Computing Machinery, Oct. 2019, pp. 1–9. [Online]. Available: https://dl.acm.org/doi/10.1145/3357251.3357588

[38] M. Drouot, N. Le Bigot, J.-L. de Bougrenet, and V. Nourrit, “Effect of Context and Distance Switching on Visual Performances in Augmented Reality,” in *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, Mar. 2021, pp. 476–477. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/9419330

[39] R. K. Lawrence, B. A. Cochrane, A. Eidels, Z. Howard, L. Lui, and J. Pratt, “Emphasizing responder speed or accuracy modulates but does not abolish the distractor-induced quitting effect in visual search,” *Cognitive Research: Principles and Implications*, vol. 8, no. 1, p. 63, Oct. 2023. [Online]. Available: https://doi.org/10.1186/s41235-023-00516-8

[40] J. M. Wolfe, “When do I Quit? The Search Termination Problem in Visual Search,” in *The Influence of Attention, Learning, and Motivation on Visual Search*, M. D. Dodd and J. H. Flowers, Eds. New York, NY: Springer New York, 2012, pp. 183–208, series Title: Nebraska Symposium on Motivation. [Online]. Available: https://link.springer.com/10.1007/978-1-4614-4794-8_8

[41] J. Moher, “Distracting Objects Induce Early Quitting in Visual Search,” *Psychological Science*, vol. 31, no. 1, pp. 31–42, Jan. 2020. [Online]. Available: https://journals.sagepub.com/doi/10.1177/0956797619886809

[42] B. T. West, K. B. Welch, and A. T. Galecki, *Linear mixed models: a practical guide using statistical software*. Chapman and Hall/CRC, 2022.

[43] L. Clark, M. E. Iskandarani, and S. Riggs, “Reaching interactions in virtual reality: the effect of movement direction, hand dominance, and hemispace on the kinematic properties of inward and outward reaches,” *Virtual Reality*, vol. 28, no. 1, p. 43, 2024.

[44] G. Horstmann, A. Herwig, and S. I. Becker, “Distractor dwelling, skipping, and revisiting determine target absent performance in difficult visual search,” *Frontiers in psychology*, vol. 7, p. 1152, 2016.

[45] G. Kyung and S. Park, “Curved Versus Flat Monitors: Interactive Effects of Display Curvature Radius and Display Size on Visual Search Performance and Visual Fatigue,” *Human Factors*, vol. 63, no. 7, pp. 1182–1195, Nov. 2021, publisher: SAGE Publications Inc. [Online]. Available: https://doi.org/10.1177/0018720820922717

[46] L. Shupp, R. Ball, B. Yost, J. Booker, and C. North, “Evaluation of Viewport Size and Curvature of Large, High-Resolution Displays,” *Graphics Interface*, pp. 123–130, Jun. 2006.