AReading with Smartphones: Understanding the Trade-offs between Enhanced Legibility and Display Switching Costs in Hybrid AR Interfaces

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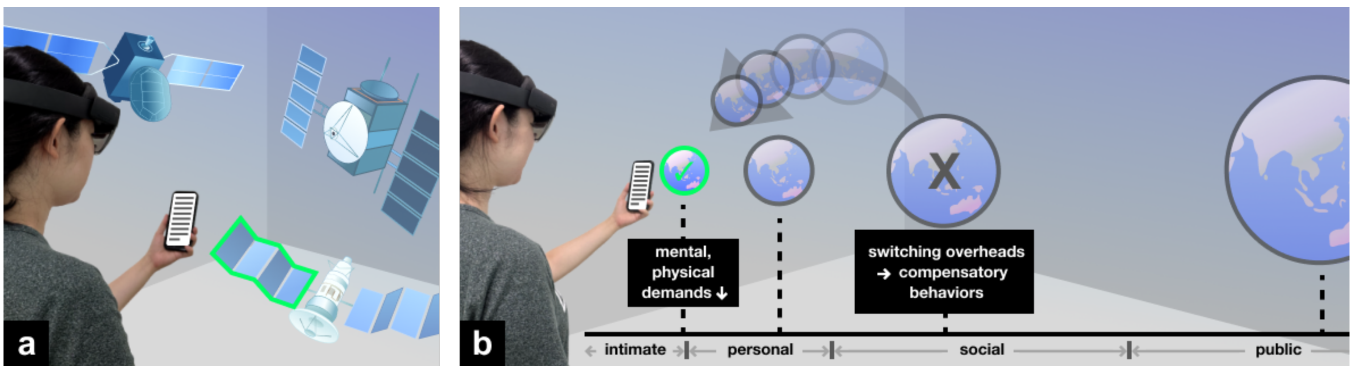

Figure 1: An illustration of the user scenario and design implications for the proposed hybrid user interface (see subsection 5.2): (a) A user in an augmented science museum reads detailed text related to a 3D virtual object, using a smartphone as a supplementary display (b) When viewing virtual content at an intimate distance, the smartphone aids in reducing mental and physical demands. However, at a social distance, compensatory behaviors emerge due to increased display switching costs, suggesting that virtual content should be moved closer to the user or that the smartphone should be utilized as an input device rather than a display in these scenarios.

Abstract

This research investigates the use of *hybrid user interfaces* to enhance text readability in augmented reality (AR) by combining optical see-through head-mounted displays with smartphones. While this integration can improve information legibility, it may also introduce display switching side effects. The extent to which these side effects hinder user experience and when the benefits outweigh drawbacks remain unclear. To address this gap, we conducted an empirical study (N=24) to evaluate how hybrid user interfaces affect AR reading tasks across different content distances, which induce varying levels of display switching. Our findings show that *hybrid user interfaces* offer significant readability benefits compared to using the *HMD only*, reducing mental and physical demands when reading text linked to content at closer distances. However, as the distance between displays increases, the compensatory behaviors users adopt to manage increased switching costs negate these benefits, making *hybrid user interfaces* less effective. Based on these findings, we suggest (1) using smartphones as supplementary displays for text in reading-intensive tasks, (2) implementing adaptive display positioning to minimize switching overhead in such scenarios, and (3) adjusting the smartphone's role based on content distance for less intensive reading tasks. These insights provide guidance for optimizing smartphone integration in hybrid interfaces and enhancing AR systems for reading applications.

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CCS Concepts

• **Human-centered computing → Mixed / augmented reality**; *User studies.*

Keywords

hybrid user interfaces, OST HMD, readability, attention switching, augmented reality

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1 Introduction

Optical see-through (OST) augmented reality head-mounted displays (AR HMDs), such as the HoloLens[1] or Magic Leap[2], have advanced rapidly in recent years, drawing attention for their ability to deliver visual experiences unattainable on other devices. However, despite advancements, OST HMDs face significant challenges for reading due to display limitations. Low angular resolution results in text legibility issues, hindering reading performance [87]. Additionally, the transparency of the displays allows background distractions [4, 96], which may further interfere with text reading. While much AR research has emphasized its immersive potential, reading remains a crucial task across many AR applications, such as web browsing [1, 71], messaging [50], virtual museum exploration [64], and office work [17, 83]. As reading is a fundamental activity across various environments [93], improving the reading experience in AR is a critical challenge that needs to be addressed.

Many studies have sought to improve text readability on OST HMDs through enhanced text design, such as using billboards [21, 29, 35] and adjusting text styles [35, 42, 52]. However, little research has explored hybrid solutions that integrates OST HMDs with physical displays to address these challenges. Leveraging smartphones as supplementary displays offers potential benefits, including improved text readability through their higher screen densities [43] and reduced background distractions with their opaque screens. Despite these advantages, using multiple displays also introduces the challenge of display switching [85], where shifting visual attention between displays often leads to longer information processing times [26, 85, 99], increased subjective workload [26, 99], and visual fatigue [3, 33] compared to single-display setups. Moreover, these effects can be intensified as the physical gap between displays increases [3, 48, 76]. This raises a key question: What are the costs associated with switching attention between AR and smartphone displays, and when do the legibility benefits outweigh these costs?

To address this question, we conducted an empirical study to evaluate how joint OST-smartphone hybrid user interfaces impact user experience in an AR reading task, where participants read text associated with a virtual image—representative of a common AR reading scenario. In a within-subjects experiment with 24 participants, we compared the *hybrid user interface* to using the *HMD only*, where participants were asked to read text linked to virtual content presented at four different distances with varying levels of distance gaps between the AR and smartphone displays. We measured task performance, perceived workload, fatigue, and viewing behaviors as dependent variables, supplemented by additional subjective ratings and qualitative feedback to gain deeper insights into participants' experiences with each condition.

Our findings show that while the *hybrid user interface* offers advantages in readability-related metrics over *HMD only*—including improved task accuracy, reduced visual fatigue, better perceived readability, and enhanced concentration—the overall user experience is strongly influenced by the distance of the virtual content. At closer distances, the higher angular resolution of the smartphone in *hybrid user interfaces* allowed participants to perform tasks with lower mental and physical effort compared to the *HMD only*. However, as the gap between the displays increased, these benefits diminished as users adopted compensatory behaviors to manage the increased switching costs. Although a larger gap did not necessarily increase visual fatigue or impair task performance, it resulted in an increased arm fatigue as participants extended their arms to reduce distance between the displays. Additionally, we observed increased difficulty in attention switching as the display gap widened, reducing the effectiveness of the *hybrid user interface*.

These findings offer valuable insights for hybrid user interfaces and provide important implications for designers and researchers focused on AR reading activities. Our results can be applied to improve a variety of AR scenarios that involve effective information retrieval, such as reading text descriptions in museums, learning in educational settings, or following instructions in various AR applications. The main contributions of our study are twofold: (1) We present key findings from an evaluation of the interaction effects between interface mode and AR content distance, encompassing performance metrics, perceived workload and fatigue, and viewing behavior. (2) Based on these findings, we propose design implications to maximize the potential of smartphones in hybrid user interfaces for AR reading scenarios.

2 Related Works

In this section, we review prior work on text readability in OST HMDs, hybrid user interfaces, and the display switching costs associated with these interfaces.

2.1 Text Readability on OST HMDs

OST HMDs face readability challenges stemming from both hardware and software limitations. Pavanatto et al. [81] identified display quality, optics, and ergonomics as key hardware concerns, and virtual screen design and its relationship with the user's viewpoint as critical software issues affecting the readability of virtual monitors on HMDs. Additionally, Bang and Woo [7] highlighted low resolution, translucency, and a restricted field of view (FOV) as primary factors contributing to poor text readability on these devices.

Screen density plays a crucial role in determining text readability [43]. Research shows that low pixel densities can result in reduced

[1]https://www.microsoft.com/en-us/hololens/
[2]https://www.magicleap.com/magic-leap-2

reading speeds [44], increased physical discomfort [67], and greater mental effort [65] when reading compared to high-density displays. These challenges are particularly pronounced when small fonts are used [8]. Most commercial near-eye displays offer an angular resolution between 10 and 15 pixels per degree (PPD), significantly below the average human visual acuity of approximately 60 PPD [16]. While devices like the HoloLens claim a higher PPD [68], studies have shown that reading speeds on these OST displays remain significantly slower compared to traditional LCD monitors, largely due to lower pixel density [87]. Additionally, a 14% decline in performance was observed when using OST displays compared to physical monitors for reading-heavy productivity tasks, primarily due to their low resolution and limited FOV [79].

In addition to resolution constraints, environmental factors also impact text readability on OST HMDs. Since these displays project virtual graphics onto a transparent screen where they blend with ambient light [15], the visibility of information is highly susceptible to lighting conditions [35] and visual distractions from the surrounding environment [4, 62]. When HMDs are used against cluttered backgrounds, users often find tasks more distracting, with a decline in subjective performance and increased cognitive load [96]. To mitigate background influence, researchers have explored various text presentation methods, such as using billboards to isolate text from the background [21, 29, 34, 52], with some studies specifically suggesting blue billboards [21, 35, 58]. Additionally, employing negative polarity [28, 52, 55, 72]—light text on a dark background, also known as dark mode—or dynamic color-correction algorithms that optimize text color [42] have been suggested for better legibility.

Beyond environmental challenges, the limited FOV of OST HMDs further constrains the readability of lengthy text. To address this, researchers have proposed dynamic text presentation methods such as rapid serial visual presentation [94], which displays text one word at a time on the HMD screen, and automatic scrolling based on user's cognitive state [104]. These techniques aim to compensate for the limited FOV, allowing users to engage with longer text more efficiently on OST HMDs.

Despite numerous efforts to improve text readability on OST HMDs through enhanced text design, a substantial readability gap remains between OSTs and physical displays [87], primarily due to the low text clarity caused by the limited angular resolution of OSTs. Furthermore, the trade-off between increasing angular resolution and expanding the FOV presents challenges in developing high-resolution HMDs [51]. To address these limitations, we explore the integration of OST HMDs with smartphones for AR reading tasks. Modern smartphones offer pixel densities of 440–570 pixels per inch (PPI) [43], equivalent to approximately 103–133 PPD at a 34 cm viewing distance [5], greatly surpassing typical HMD PPD [16]. Building on research suggesting that higher pixel densities improve reading speed [44] while reducing physical fatigue [67] and mental effort [65], we hypothesize that leveraging smartphones as supplementary displays can provide these benefits in AR reading tasks.

2.2 Hybrid User Interfaces

The concept of *hybrid user interfaces* was first introduced by Feiner and Shamash [31], who described it as the combination of "heterogeneous display and interaction device technologies [to] take advantage of the strong points of each". In their work, they proposed a hybrid user interface which combines small, high-resolution conventional devices with HMDs that provide larger but lower-resolution displays. Since then, various hybrid user interfaces have been proposed, integrating AR HMDs with complementary devices such as smartphones [37, 56, 77, 95, 100], smartwatches [37, 63], tablets [46, 60], desktop monitors [80, 82, 83, 108], wall displays [49, 90], and tabletops [84, 89].

A significant body of research has examined the integration of AR HMDs with smartphones to leverage their precise and tactile input capabilities alongside familiar interaction patterns [111]. Studies have utilized smartphone touchscreens and inertial sensors to enhance a range of interactions, including pointing and target selection [11, 74, 100], virtual object [56, 61, 74] or window manipulation [91], menu navigation [95], and GUI control [56, 109]. Additionally, smartphone input has been used to support tasks such as text entry and selection [20, 39], data analytics [12, 45, 46, 105], and even complex applications like 3D modeling [73].

Other studies have explored combining the spatial capabilities and large information space of AR HMDs with the higher resolution of smartphone displays to create enhanced display environments [111]. One approach involves virtually extending the smartphone's screen onto the HMD [6, 47, 77, 88, 102], enabling the offloading of content such as long lists [106], annotations [22], and instructional guides [53]. Another approach uses smartphones to compensate for the lower display fidelity of HMDs. For instance, smartphones can be used to provide higher visual detail to the HMD content [37], or to display high-resolution 2D graphs alongside low-resolution holographic 3D charts, thereby enhancing data visualization [18]. Additionally, smartphones have been employed as supplementary displays to offload long text from AR HMDs [7], reducing task load, alleviating visual fatigue, and enhancing reading comfort—an approach closely aligned with our research.

Prior research on hybrid user interfaces highlights the potential of combining physical displays with HMDs to enhance information readability in AR [7, 30]. However, the use of multiple displays also introduces perceptual challenges due to attention shifts between displays with differing resolution, luminance, visual fidelity, interference, color, and contrast [38]. Research on transitional interfaces [13] further underscore these difficulties, identifying continuity issues inherent when transitioning between different environments in hybrid setups. In particular, perceptual discontinuities become especially noticeable during display transitions. While these challenges are acknowledged, their specific impact on AR reading remains unexplored. Our research addresses this gap by investigating the trade-offs between the legibility benefits provided by smartphones and the perceptual costs associated with attention switching in multi-display setups. Specifically, we aim to identify the conditions under which legibility advantages outweigh switching costs, and vice versa, an area yet to be studied.

2.3 Display Switching Costs in Hybrid User Interfaces

Distributing visual output across multiple displays imposes additional demands on users, commonly referred to as *display switching costs* [85], as they shift visual attention between different screens. These attention shifts often accompany adjustments in cognitive focus, gaze, and even head or body position due to the limited focus area of human vision [86]. Display switching can cause significant performance overhead in hybrid setups as users adapt their gaze to displays with varying depths, resolutions, and sizes [85]. Additionally, the spatial separation of information can increase cognitive load as users attempt to mentally integrate the disparate sources of information [101]. Cauchard et al. [14] described this division of information as visual separation, highlighting its effects as an inherent drawback of multi-display settings.

Several factors can intensify display switching costs, including differences in display depth relative to the user [103] and significant angular separation between displays, which can increase task completion time and subjective workload [99]. Greater physical distance between displays can further extend the time required for certain tasks [76]. Additionally, displays positioned outside the same visual field can alter visual attention behaviors, necessitating more neck and head movement over simple gaze shifts, thereby increasing switching effort [14]. Features such as bezels between displays have also been shown to hinder performance in tasks like tunnel steering [9]. Other contributing factors include content coordination, input directness (the match between the input device and the action performed), and input-display correspondence (the alignment between input and output devices) [86].

Attention switching costs have also been explored in the context of AR. Eiberger et al. [26] found that using OST HMDs in conjunction with body-proximate displays (e.g., smartphones or smartwatches) significantly impairs visual search performance and increases subjective workload due to the need to process information at multiple depth layers. Given that most commerical OST HMDs have a fixed focal distance [33] (typically ranging from 1.25 to 2 m [70]), switching between different depths becomes unavoidable in interfaces that integrate OST HMDs with handheld displays. Studies have shown that within OST displays, both *context switching* between the virtual and real-world [3, 33] and *focal distance switching* [3, 25, 33]—adjusting the eyes to different focal distances—can lead to increased visual fatigue and decreased search performance. Larger switching distances further intensify these effects [3]. Similarly, when users switch context between a real-world task and a virtual display, both task completion time and user discomfort tend to increase as the virtual information is positioned further away from the real-world task [48].

In summary, prior research suggests that switching attention between virtual and physical displays in hybrid user interfaces can negatively impact visual task performance [26, 33], increase subjective workload [26], and heighten visual fatigue [3, 33], with larger gaps between displays amplifying these effects [3, 48]. However, it is yet unknown how varying display gaps in hybrid AR interfaces impact reading tasks. In AR, reading tasks can occur across various spatial scales [69], resulting in differing distance gaps between virtual content on HMDs and smartphone displays when smartphones are used as supplementary displays. For instance, reading text while interacting with a nearby virtual model involves a smaller gap between displays, whereas reading text associated with a distant virtual object creates a much larger gap. Building on prior work, we hypothesize that larger spatial gaps—where virtual content on the HMD and smartphone displays are positioned in distinct spatial zones—will place greater demands on attention switching [13] compared to scenarios where the displays are in closer proximity (i.e., within the same spatial zone). To explore this further, our study focuses on investigating readability benefits and attention-switching costs of using smartphones for reading tasks across varying spatial zones—intimate, personal, social, and public—defined based on Hall's theory of proxemics [40].

3 Methodology

By integrating OST HMDs with smartphone displays, we can leverage the smartphone's higher angular resolution to overcome the legibility limitations of OST HMDs, making hybrid interfaces effective for reading detailed text in AR environments. However, this approach introduces potential drawbacks, particularly with attention switching between the virtual and physical displays, as switching between non-contiguous displays can negatively impact both performance and subjective experience, especially as the physical gap between the displays increases. To investigate the balance between legibility benefits and attention switching costs, we evaluate hybrid user interfaces with varying virtual content distances on the HMD, creating different display gaps between AR and smartphone screens.

3.1 Research Questions and Hypotheses

Our study aimed to explore the following research questions for AR reading tasks:

RQ1. How does task performance differ between a hybrid user interface and an HMD-only setup across varying virtual content distances?

RQ2. How do perceived workload factors differ between a hybrid user interface and an HMD-only setup across varying virtual content distances?

RQ3. How do users' viewing behaviors differ between a hybrid user interface and an HMD-only setup across varying virtual content distances?

To address our research questions, we developed the following hypotheses based on our review of related literature:

H1-1. The hybrid user interface will enhance task performance compared to the HMD-only setup when virtual content is within the intimate distance.

H1-2. When virtual content is beyond the intimate distance, task performance will either show no difference between the interface modes or favor the HMD-only setup.

H2-1. The hybrid user interface will reduce perceived workload factors compared to the HMD-only setup when virtual content is within the intimate distance.

H2-2. When virtual content is beyond the intimate distance, perceived workload factors will either show no difference between the interface modes or favor the HMD-only setup.

H3. The effects of interface modes on viewing behaviors will vary across different content distances.

We hypothesized that the hybrid user interface would outperform the HMD-only setup in AR reading tasks when the virtual content and the smartphone display are within the same spatial zone (i.e., the intimate distance, as smartphones are typically held at this range), primarily due to the smartphone's higher pixel density, especially improving reading speed [44] (**H1-1**). However, as virtual content moves beyond the intimate distance, increasing the gap between the AR and smartphone displays, we anticipated that attention shifts between distinct spatial zones would prolong information processing times, thereby negating the benefits of the smartphone display (**H1-2**).

Similar trends were hypothesized for perceived workload factors. Specifically, when AR content is within the same spatial zone as the smartphone display, we expected the smartphone's higher screen density to reduce the mental effort required for reading [65]. Additionally, the smartphone's opaque display, while only marginally effective given that study's uncluttered background, was anticipated to mitigate background distractions, potentially alleviating cognitive load [96] (**H2-1**). In contrast, as virtual content moves beyond the intimate distance, larger display gaps were expected to increase visual fatigue [3] and discomfort [48], thereby raising physical demand. Furthermore, the need to integrate spatially separated information was expected to impose additional cognitive load on users in these contexts [101] (**H2-2**).

Lastly, we hypothesized that the increased attention-switching challenges in hybrid interfaces for distant content would lead to distinct viewing behaviors, influencing attention patterns, smartphone-holding postures, and head rotations (**H3**).

3.2 Independent Variables

We used a 2×4 factorial design for the user experiment, with two independent variables: interface mode (*HMD only*, *hybrid*) and AR content distance (*0.45 m*, *1 m*, *2 m*, *5 m*), both as within-subject factors (see Figure 2). In the *HMD-only* condition, both the virtual image content and associated text were displayed on the HMD, serving as the baseline. In the *hybrid* condition, the virtual image content remained on the HMD, but the associated text was displayed on a smartphone.

The AR content distance levels were designed to align with distinct proxemic zones around the user, as proposed by Hall [40]. These zones were originally developed to describe interpersonal distances and have since been adapted for user-device interactions [23, 66]. Content placed at *0.45 m* falls within the intimate distance (0–0.46 m) and aligns with the smartphone's typical viewing range, requiring minimal display-switching effort between image and text in the *hybrid* setup. Content at *1 m* lies within the personal distance (0.46–1.22 m), *2 m* in the social distance (1.22–3.66 m), and *5 m* in the public distance (beyond 3.66 m). As the distance increases, the gaps between displays in the *hybrid* setup grow larger, likely resulting in greater attention-switching overheads that negatively affect the user experience. On the other hand, *2 m* is known to be the optimal reading distance for the HoloLens, as it aligns with its focal plane, with distances closer than that potentially resulting in visual fatigue due to vergence-accommodation conflict [70].

In the *HMD-only* condition, the distance between the image and text remained consistent as distance levels changed, but in the *hybrid* condition, this distance varied (see Figure 2b). This variation occurred because, while AR HMDs can adjust text placement to align with image content, smartphones are typically held at a fixed viewing distance of around 34 cm [5]. Although replicating similar image and text panel positions in the *HMD-only* setup was possible (e.g., by positioning the text panel at arm's reach), we opted against this approach as we considered it an unlikely scenario for AR environments, where text labels are commonly placed near their referent objects [75]. Our focus was on understanding when a hybrid user interface is beneficial versus when it is not, and on finding practical solutions for AR reading. Consequently, significant display gaps emerged in the *hybrid* condition, especially when the AR content was positioned at farther distances on the HMD.

3.3 Experimental Task

For our experiment, we designed a task that meets the following criteria: (1) It involves both text reading and context switching between text and virtual imagery, allowing us to evaluate the interplay between enhanced readability and the switching costs associated with smartphone use. (2) It enables measurement of task completion time and errors. (3) It is abstract rather than realistic, eliminating the influence of participants' prior background knowledge. (4) It reflects typical AR reading scenarios. To achieve this goal, we adapted a comparison task previously used to quantify switching costs [14, 25, 103]. Instead of using simple text or image comparisons as in prior studies, we modified the task to have participants to compare an image with its corresponding textual description. We believe this task offers ecological validity, as it mirrors real-world situations, such as reading artwork descriptions in a virtual museum, similar to scenarios explored in prior studies [7, 93].

In the task, participants were presented with an image panel on the left-hand side of the HMD and a text panel either on the right-hand side of the HMD or on the smartphone, depending on the interface condition they were experiencing, as shown in Figure 2. The goal was to compare the text descriptions against the image content and identify how many incorrect descriptions were present. Participants had to then enter the number of mismatched sentences into a keypad placed in front of them.

The image consisted of 12 different shapes randomly placed within a 12×5 grid. These shapes were generated using a combination of five shape types (*circle*, *triangle*, *square*, *pentagon*, or *star*), five colors (*red*, *yellow*, *green*, *blue*, or *pink*) and two patterns (*filled* or *outlined*). The text panel contained 12 sentences, each describing one of the shapes in the image. For example, a sentence might read, *"In row 5, column E, there is a triangle with a green outline."* To eliminate any input-related effects, the text was limited to 12 sentences, ensuring it fit within the smartphone screen without requiring scrolling. The sentences were grouped into four paragraphs, with three sentences per paragraph, and the order of the paragraphs was randomized to increase task difficulty. To maintain a consistent level of difficulty, all sentences followed the same structural format.

Incorrect descriptions contained inaccuracies regarding either the color or pattern of the shapes, with each trial including one to

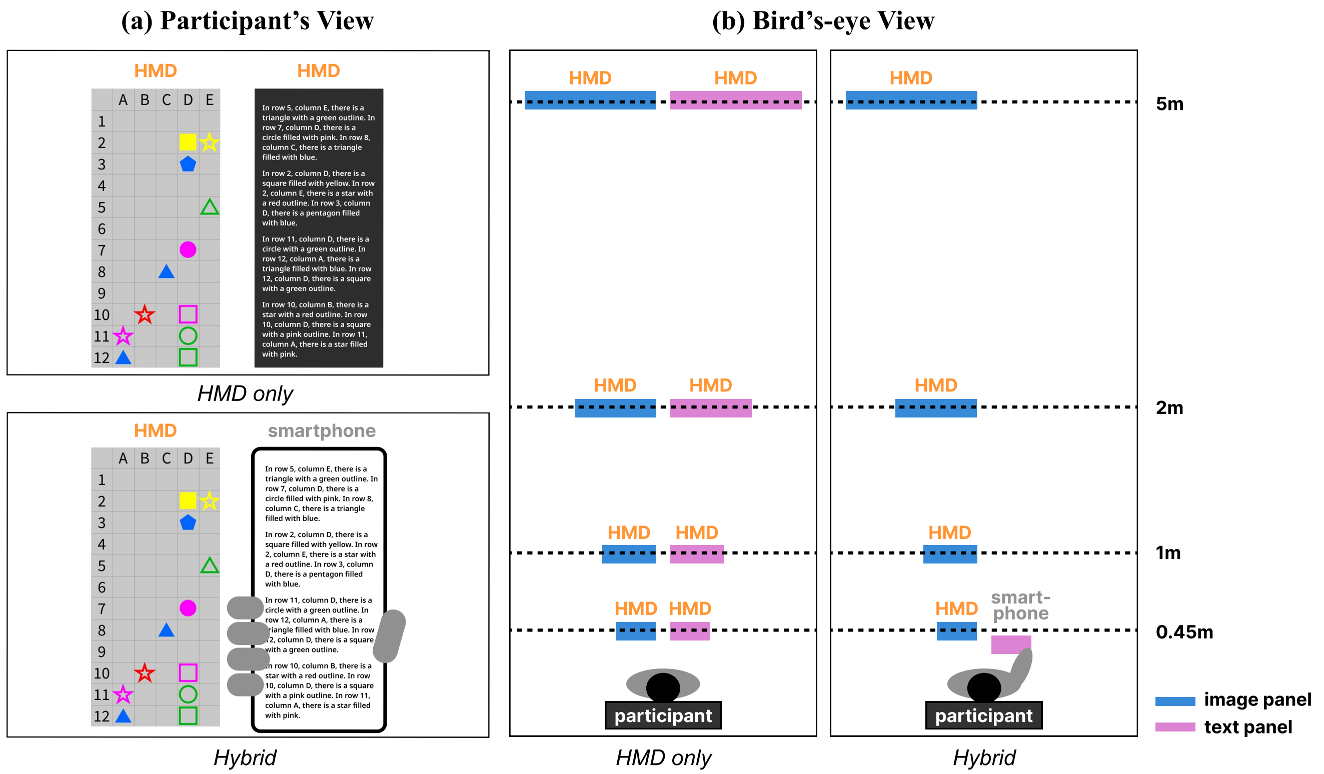


Figure 2: An illustration of the study conditions consisting of two interface modes (*HMD only*, *hybrid*) and four content distances (*0.45 m*, *1 m*, *2 m*, *5 m*), shown from (a) the participant's view and (b) a bird's-eye view. In the experimental task, text was presented in the local language rather than in English.

three incorrect sentences. Through pilot testing, we confirmed that all shapes and colors was easily distinguishable. Based on feedback from these tests, we also made several adjustments to ensure better consistency in difficulty across the experimental stimuli. First, each paragraph was restricted to containing no more than one incorrect sentence. Second, we chose to inform participants that there could be up to five incorrect sentences, even though each trial actually contained only one to three. This strategy aimed to encourage participants to read the entire text, even after identifying all the incorrect sentences. To further minimize bias from task difficulty, we rotated the stimuli sets across conditions for different participants. Each condition consisted of three trials, resulting in a total of 24 trials per participant. Additionally, the text was presented in Korean, taking into account the demographics of the participants to be recruited.

Due to the differing display characteristics of the HMD and smartphone, applying identical text settings across both devices was not feasible. However, we strived to maintain consistency in factors such as font, size, and line spacing throughout the different device conditions (see Table 1). Text styles—including font [110], size [2, 36, 72], line spacing [7], color [28, 55, 72], viewing angle [70], and reference frame [10, 32]—were established based on guidelines from previous studies, Microsoft HoloLens [70, 72], Material Design [36] and iOS Human Interface Guidelines [2]. Other parameters were optimized for each display individually, as applying them uniformly would have disadvantaged one condition or another. For example, universally applying dark mode would have penalized the smartphone condition, as dark mode slows reading on smartphones [78]. Conversely, using light mode (dark text on a light background) across both displays would have significantly hindered the HMD condition, as light mode impairs visual acuity and comfort on OST HMDs [28, 55]. Consequently, text and background colors varied between display conditions.

Furthermore, we used angular size [24] rather than physical size to set text and panel dimensions. This ensured that the perceived size of stimuli remained constant across different distance conditions, avoiding any impact of text size on readability.

3.4 Dependent Variables

As dependent variables, we focused on three key metrics—task performance, workload and fatigue, and viewing behavior—to address our research questions. To assess the impact of interface mode and content distance on task performance, we measured task completion time and number of errors. Task completion time was recorded in seconds from the start to the end of each trial, as initiated by the participant via the keypad. The number of errors was calculated as the absolute difference between the correct target count and

Table 1: Text settings used on each device.

	HMD	Smartphone
Font	Noto Sans	Noto Sans
Font Size	0.5°	0.5° (at a viewing distance of 34cm)
Line Spacing	140 %	140 %
Text Color	White (RGB: 255, 255, 255)	Black (RGB: 0, 0, 0)
Background Color	Dark Grey (RGB: 37, 37, 37)	White (RGB: 255, 255, 255)
Text panel size	13.07°× 27.01°	13.07°× 27.01° (at a viewing distance of 34cm)
Viewing Angle	-15°	N/A
Reference frame	World-fixed	Screen-fixed

the participant's reported target count, with target counts ranging from one to three for each trial.

To evaluate workload and fatigue, we used the raw NASA TLX [41] to measure perceived workload and collected subjective responses on visual and arm fatigue after participants completed each block. In the NASA TLX, we excluded the temporal demand subscale, as it was not relevant to our study, and focused on the remaining dimensions: mental demand, physical demand, performance, effort, and frustration. Participants rated their responses on a scale from 0 to 100 in 5-point increments. Visual fatigue was assessed using a 7-point Likert scale, ranging from *very rested* to *very fatigued*, following the approach used by Arefin et al. [3], with arm fatigue assessed in the same way.

Regarding viewing behavior, we collected data on participants' visual attention, smartphone-holding posture, and head movements. For visual attention, we used the HoloLens 2's built-in eye-tracking cameras (60 Hz) to capture gaze origin and direction. Using this data, we cast a gaze ray to estimate which panel (text or image) participants were looking at in each frame. This enabled us to track how frequently participants shifted their gaze between the panels, as the number of gaze shifts can indicate attention-switching difficulty [14]. We divided the total number of gaze shifts by task duration to compare gaze shifts per second across conditions. Additionally, we recorded the time each participant spent looking at each area of interest (AOI)—the text and image panels—to analyze attention patterns.

To understand how participants adjusted their smartphone-holding posture across different interface modes and distance conditions, we collected data on the average smartphone position during each trial and the distance the phone traveled during the task, divided by task duration. The smartphone position was logged relative to the initial head position, and data was recorded only during the *hybrid* condition. We also measured head rotation per second and the range of head movement along each axis to evaluate physical costs of each condition [83]. Head rotation per second was calculated by dividing the cumulative angular distance from tracked head movements by the total task duration. All behavioral data was logged at 60 frames per second.

Furthermore, we collected subjective insights using 7-point Likert scale ratings on readability and concentration. Participants were asked to rate the following statements: "I could easily read the information on the display" and "I found it easy to concentrate on the task." Additionally, we gathered qualitative feedback after each session by asking participants to share their experiences with each interface and how content distance influenced their overall experience. All questionnaires used in the study are provided in Appendix A.

3.5 Apparatus

We used the Microsoft HoloLens 2 as the AR HMD for both interface conditions, as it offers one of the highest display qualities available for an OST display. The device has a diagonal field of view of 52°, a screen resolution of 2048 × 1080 pixels per eye with 47 PPD [68], and over 2.5k light points per radian. For the *hybrid* condition, we used Samsung Galaxy S22 Ultra[3] as the smartphone. This smartphone has a 6.8-inch display with a resolution of 1440 × 3088 pixels and 500 PPI (approx. 117 PPD, assuming a viewing distance of 34cm [5]), weighing 229g. The software for both devices were developed in Unity[4] 2021.3.31f1. using the Mixed Reality Toolkit (MRTK)[5] version 3.0.0. Photon Unity Networking (PUN)[6] plugin was used to synchronize events between the HMD and the smartphone.

Both the HMD and the smartphone had retro-relective markers attached to them, tracked by OptiTrack[7] cameras mounted on the room's ceilings. This external tracking system allowed us to spatially monitor the devices throughout the task, collecting their movement data and determining when participants viewed the phone screen. We gathered the tracked position and orientation of the devices through the Motive[8] software, and streamed it to the HMD application via OptiTrack Unity Plugin[9], where it was subsequently logged.

The study was conducted in an empty studio with white walls and uniform lighting. During the task, participants sat in a chair with a table in front of them, which had a keypad placed on top. Throughout the task, the participants were instructed to hold the phone in their right hand in portrait orientation, ensuring that the text appeared on the right side for both interface conditions.

3.6 Participants and Procedure

We recruited 24 participants (9 female, 15 male) aged 20–33 (M = 24.17, SD = 3.14) from the local university through an online

[3]https://www.samsungmobilepress.com/media-assets/galaxy-s22-ultra
[4]https://unity.com/
[5]https://learn.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/
[6]https://www.photonengine.com/PUN
[7]https://optitrack.com/
[8]https://optitrack.com/software/motive/
[9]https://docs.optitrack.com/plugins/optitrack-unity-plugin

advertisement. Most of the participants were undergraduate and graduate students. All participants had normal or corrected-to-normal vision and spoke Korean as their native tongue, meaning they could read and fully understand the text stimuli used for the experimental tasks. Prior experience with AR headsets were mixed: 12 (50%) had never used an HMD before, 8 (33.34%) had used one up to three times, and 4 (16.67%) had used one between four and ten times through user studies or AR games.

Upon arrival, participants signed a consent form for their participation in the study and collection of their experimental data. They then filled out a demographic questionnaire and received an introductory presentation, supported by slides, detailing the study procedure and task. Researchers assisted participants in wearing the HMDs, after which participants completed the HoloLens eye calibration procedure and underwent a training session to familiarize themselves with the task in each interface mode. Once participants felt comfortable with the task, we proceeded to the main experimental session.

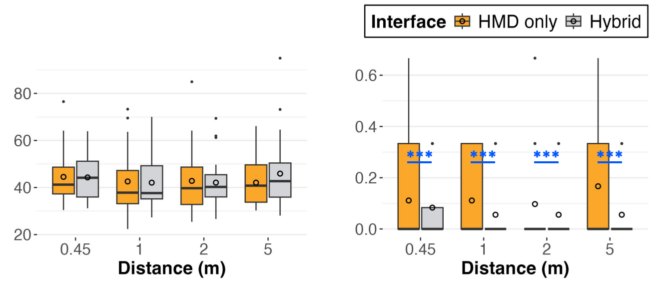
Due to the potentially high eye strain associated with the task, we divided the experimental session into two parts. Participants first completed four conditions, took a three-minute break, and then finished the remaining four conditions. Each participant started with one of eight conditions, performing three repetitions per condition. To counterbalance any potential order effects, we employed a balanced Latin Square to generate eight unique sequences of the conditions. Participants were then randomly assigned to one of eight groups, with each group following a different sequence derived from the balanced Latin Square. Throughout the task, participants remained seated at a table, using the keypad to start and end each trial and to input their answers. After each condition, participants completed a raw NASA TLX [41] and additional questionnaires assessing visual fatigue, arm fatigue, readability, and concentration.

After completing all conditions, participants filled out a final questionnaire, providing qualitative feedback on their experiences with each interface and the impact of distance on their overall experience. The study lasted 50 to 80 minutes per participant, and all participants received monetary compensation. The study's content and procedures were approved by the university's Institutional Review Board.

4 Results

In our analysis of objective data, we first assessed the normality of the data distribution using the Shapiro-Wilk test. For data that met the normality assumption ($p > .05$ for all conditions), Mauchly's test was used to check for sphericity ($p > .05$ for all effects). Where sphericity was violated, Greenhouse-Geisser corrections were applied. A two-way repeated measures ANOVA was then conducted to examine the interaction effect between interface mode and content distance, as well as their main effects. Post-hoc analyses were performed using pairwise t-tests with p-values adjusted via Bonferroni correction.

For non-normally distributed data, we used the aligned rank transform (ART) [107] prior to conducting repeated measures ANOVA. ART preprocesses data by aligning and ranking, allowing for the subsequent application of standard parametric tests. This method has been widely adopted in HCI research since its introduction [27], as it enables multi-factorial non-parametric analyses and accommodates both continuous and ordinal variables [107]. Following ART ANOVA, post-hoc comparisons were performed using the ART-C procedure [27] with Bonferroni-adjusted p-values. Both ART and ART-C procedures were implemented using the ARTool R package [54]. The same non-parametric approach was also applied to analyze all subjective data.



(a) Task Completion Time (s) **(b) Number of Errors**

[I]

Figure 3: Results for (a) Task completion time in seconds and (b) Number of Errors. The letter in brackets indicates significant findings (I × D: interaction between interface and distance, I: interface, D: distance).

Throughout our analysis, an α level of .05 was set for determining statistical significance. Effect sizes are reported using partial eta squared (η_p^2) and interpreted according to Cohen's guidelines [19]: small (.01), medium (.06), or large (.14).

Below, we summarize the key statistical results from our study:

1. There was no significant difference in task completion time between the interface conditions, but task accuracy was higher for the *hybrid* condition compared to *HMD only* across all distances.
2. Using the *hybrid* condition significantly reduced visual fatigue and improved perceived readability and task concentration across all distances compared to using the *HMD only*.
3. At a content distance of *0.45 m*, the *hybrid* condition led to significantly lower mental and physical demand compared to *HMD only*, with no significant differences between the interfaces beyond that distance.
4. Visual fatigue was notably higher at *0.45 m* than at other distances for both interfaces.
5. The *hybrid* condition resulted in greater arm fatigue than the *HMD only* across all distances, with more pronounced fatigue at *2 m* and *5 m* compared to *0.45 m*.
6. When using the *hybrid* condition, participants held the phones significantly further along the z-axis when content was at *2 m* compared to *0.45 m*.
7. When viewing content at *2 m*, participants shifted their gaze between panels fewer times with the *hybrid* condition than with the *HMD only*.

4.1 Task Performance

Task Completion Time. No significant interaction effect between interface mode and content distance on task completion time was observed ($F_{3,69}$ = .276, p = .842, η_p^2 = .012). Moreover, no main effects of neither interface mode ($F_{1,23}$ = .268, p = .609, η_p^2 = .012) nor content distance ($F_{3,69}$ = 2.599, p = .059, η_p^2 = .101) were found. On average, participants completed tasks faster with *hybrid user interfaces* compared to *HMD only* at content distance conditions of *0.45 m* (*HMD only*: M = 44.516s, SD = 11.241s; *hybrid*: M = 44.298s, SD = 9.256s), *1 m* (*HMD only*: M = 42.582s, SD = 13.420s; *hybrid*: M = 42.063s, SD = 11.048s), and *2 m* (*HMD only*: M = 42.808s, SD = 14.184s; *hybrid*: M = 42.094s, SD = 10.515s), but slower at *5 m* (*HMD only*: M = 42.086s, SD = 10.304s; *hybrid*: M = 45.910s, SD = 15.165s) (see Figure 3(a)).

Number of Errors. A significant main effect of interface mode on the number of errors was observed ($F_{1,23}$ = 37.664, p < .001, η_p^2 = .621). The *hybrid user interface* (*0.45 m*: M = .083, SD = .147; *1 m*: M = .056, SD = .127; *2 m*: M = .056, SD = .127; *5 m*: M = .056, SD = .127) consistently resulted in a lower error rate for the comparison task compared to using the *HMD only* (*0.45 m*: M = .111, SD = .188; *1 m*: M = .111, SD = .161; *2 m*: M = .097, SD = .208; *5 m*: M = .167, SD = .26) across all distance conditions. We found neither a main effect of content distance ($F_{3,69}$ = .680, p = .399, η_p^2 = .029) nor an interaction effect between interface mode and content distance ($F_{3,69}$ = .959, p = .417, η_p^2 = .040).

4.2 Perceived Workload and Fatigue

Perceived Workload. The results for the different subscales of perceived workload are shown in Figure 4(a)-(e). We found significant interaction effects between interface mode and content distance for mental demand ($F_{3,69}$ = 4.648, p = .005, η_p^2 = .168). Post-hoc tests revealed that the *hybrid* condition resulted in significantly lower mental demand compared to the *HMD-only* condition at a content distance of *0.45 m* (p = .016), while no significant differences between interface modes were found at other distances. The *HMD-only* condition also showed significantly higher mental demand at *0.45 m* compared to *1 m* (p = .034), *2 m* (p < .001), and *5 m* (p = .014). Additionally, we found a main effect of content distance ($F_{3,69}$ = 3.167, p = .0298, η_p^2 = .121), with significantly higher mental demand at *0.45 m* compared to *2 m* (p = .028). No main effect of interface was detected on mental demand ($F_{1,23}$ = 4.204, p = .052, η_p^2 = .155).

Physical demand showed a similar trend. Significant interaction effects between interface mode and content distance were found ($F_{3,69}$ = 7.187, p < .001, η_p^2 = .238). Post-hoc analysis revealed significantly lower physical demand for the *hybrid user interface* compared to using *HMD only* at *0.45 m* (p = .007), but not at other distances. The *HMD only* also showed significantly higher physical demand at *0.45 m* compared to *1 m* (p = .019), *2 m* (p < .001), and *5 m* (p = .003). A main effect of content distance was also found ($F_{3,69}$ = 3.958, p = .012, η_p^2 = .147), with higher physical demand at *0.45 m* compared to *2 m* (p = .012). No main effect of interface mode was observed on physical demand ($F_{1,23}$ = .875, p = .359, η_p^2 = .037).

We found no main effects of interface mode ($F_{1,23}$ = .002, p = .964, η_p^2 < .001) or content distance ($F_{3,69}$ = 1.797, p = .156, η_p^2 = .072), nor any interaction effects between factors ($F_{3,69}$ = 1.564, p = .206, η_p^2 = .064) for performance. Similarly, we did not detect any significant main effects of interface ($F_{1,23}$ = .044, p = .836, η_p^2 = .002) or distance ($F_{3,69}$ = 1.759, p = .163, η_p^2 = .071), or any interaction effects ($F_{3,69}$ = 1.630, p = .190, η_p^2 = .066) for effort.

For frustration, we found a significant interaction effect between interface mode and distance ($F_{3,69}$ = 4.963, p = .004, η_p^2 = .177), but no main effects of interface mode ($F_{1,23}$ = .288, p = .597, η_p^2 = .012) or content distance ($F_{3,69}$ = 1.462, p = .233, η_p^2 = .060). Significantly higher frustration was detected at *2 m* compared to *0.45 m* (p = .024) when using the *HMD only*. However, no significant differences in frustration were found among distance conditions for the *hybrid* interface. Additionally, the choice of interface had no significant effect on frustration at any distance level.

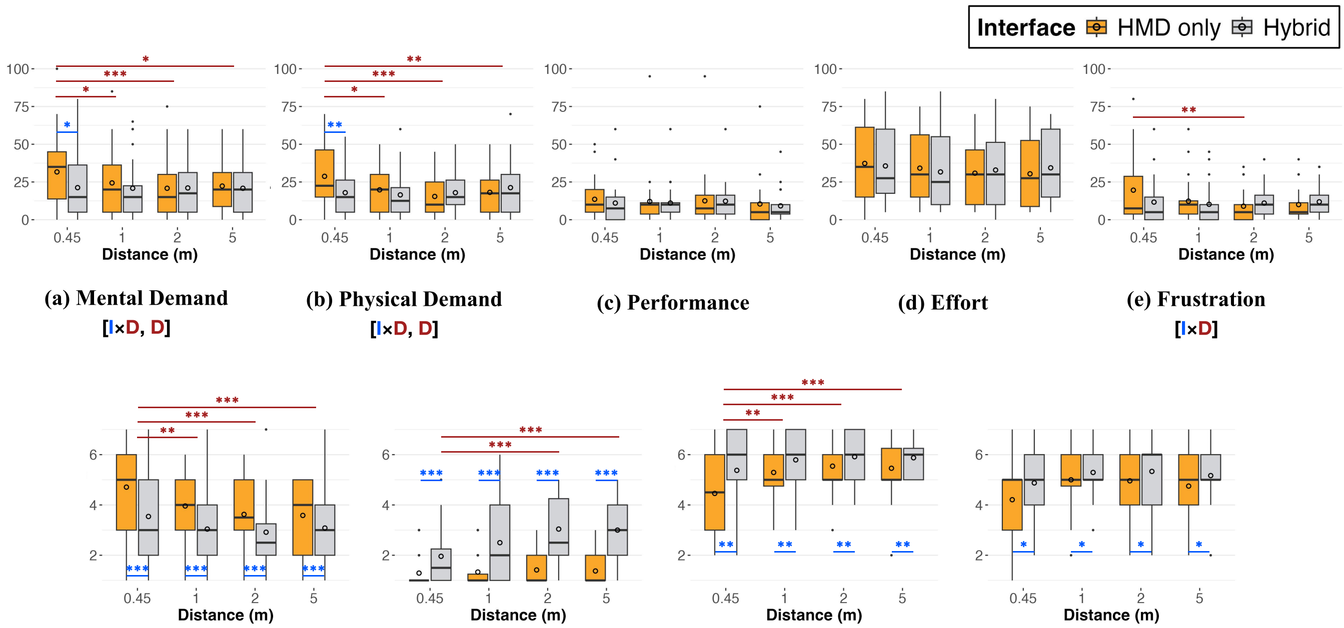
Visual Fatigue. A significant main effect was observed for both interface mode ($F_{1,23}$ = 19.543, p < .001, η_p^2 = .459) and content distance ($F_{3,69}$ = 11.363, p < .001, η_p^2 = .331) on visual fatigue (see Figure 4(f)). Pairwise post-hoc comparisons showed that the *hybrid* condition resulted in significantly lower visual fatigue compared to the *HMD-only* condition. Moreover, content placed at *0.45 m* from the user produced significantly higher visual fatigue compared to placements at *1 m* (p = .004), *2 m* (p < .001), or *5 m* (p < .001). No interaction effect between interface mode and content distance was detected ($F_{3,69}$ = .722, p = .542, η_p^2 = .03).

Arm Fatigue. There was a statistically significant interaction effect between the interface mode and content distance on arm fatigue ($F_{3,69}$ = 8.384, p < .001, η_p^2 = .267) (see Figure 4(g)). Analyzing the effect of content distance for each interface mode, we found significantly higher arm fatigue at *2 m* (p < .001) and *5 m* (p < .001) compared to *0.45 m* in the *hybrid* condition, but no differences among distance conditions for the *HMD only*. We also detected main effects for both interface mode ($F_{1,23}$ = 33.924, p < .001, η_p^2 = .596) and content distance ($F_{3,69}$ = 11.719, p < .001, η_p^2 = .338). As expected, the *hybrid* condition resulted in higher arm fatigue across all distance conditions. For content distance, pairwise comparisons revealed lower arm fatigue when content was placed at *0.45 m* from the user compared to *2 m* (p < .001) and *5 m* (p < .001), and also at *1 m* compared to *5 m* (p = .036).

4.3 Viewing Behavior

Although not a primary focus of our study, we also analyzed the effects of trial on behavioral data to identify any differences across the three trials. Data from one of the 24 participants was excluded from the gaze shift and AOI analysis due to incomplete gaze logs.

Number of Gaze Shifts. The analysis of gaze shifts between panels revealed a significant interaction effect between interface mode and content distance ($F_{3,66}$ = 2.876, p = .043, η_p^2 = .116) (see Figure 5(a)). A post-hoc test for simple effects showed fewer gaze shifts per second in the *hybrid* condition compared to the *HMD-only* condition at a distance of *2 m* (p = .012), but no significant differences between interfaces at other distances. No main effect of interface mode ($F_{1,22}$ = 1.236, p = .278, η_p^2 = .053) or content distance ($F_{3,66}$ = .261, p = .853, η_p^2 = .012) was found on the number of gaze shifts. Also, we did not find any effect of trial on the gaze shifts ($F_{1,22}$ = 2.826, p = .07, η_p^2 = .114)



(a) Mental Demand
[I×D, D]

(b) Physical Demand
[I×D, D]

(c) Performance

(d) Effort

(e) Frustration
[I×D]

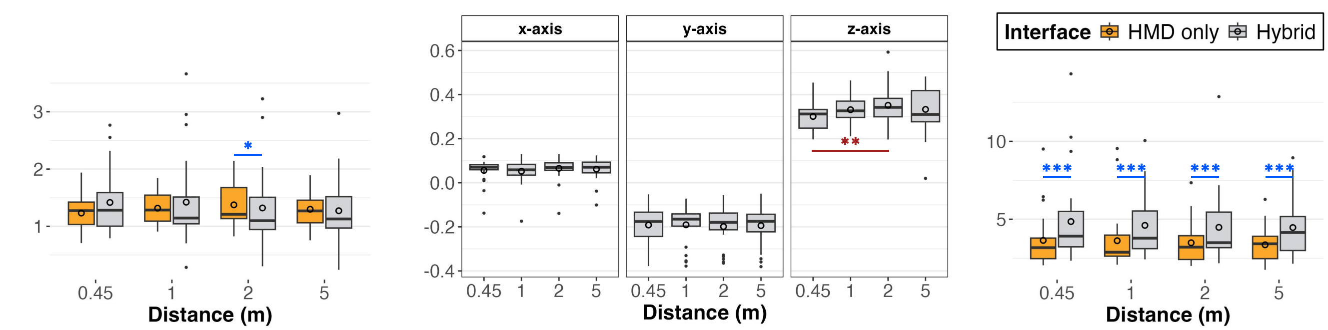
(f) Visual Fatigue
[I, D]

(g) Arm Fatigue
[I×D, I, D]

(h) Perceived Readability
[I, D]

(i) Concentration
[I]

Figure 4: Results for (a)-(e) Subscales of perceived workload (f)-(g) Fatigue, and (h)-(i) Additional subjective ratings. The letter in brackets indicates significant findings (I × D: interaction between interface and distance, I: interface, D: distance).



(a) Number of Gaze Shifts Per Second
[I×D]

(b) Average Smartphone Position (m)
[D]

(c) Head Rotations Per Second (°/s)
[I]

Figure 5: Results of (a) Number of gaze shifts per second, (b) Average smartphone position in meters (x = right, y = up, z = forward toward the panels), and (c) Head rotation in degrees per second. The letter in brackets indicates significant findings (I × D: interaction between interface and distance, I: interface, D: distance).

AOI Analysis. An AOI analysis comparing gaze duration in each AOI—the image panel and text panel—revealed significant differences in visual attention patterns between conditions (see Figure 6). For the gaze duration on text panel, we found a significant main effect of interface mode ($F_{1,22} = 22.142$, $p < .001$, $\eta_p^2 = .502$). Participants gazed at the text panel for a significantly shorter time in the *hybrid* condition compared to the *HMD-only* condition. We also found a main effect of trial on the gaze duration on text panel ($F_{2,44} = 4.074$, $p = .023$, $\eta_p^2 = .156$), with gaze duration being shorter in trial 2 compared to trial 1 ($p = .030$).

Conversely, for the image panel, we found the opposite results ($F_{1,22} = 15.361$, $p < .001$, $\eta_p^2 = .411$). Participants spent significantly more time gazing at the image panel in the *hybrid* condition compared to the *HMD-only* condition. Additionally, there was a main effect of distance on gaze duration for the image panel ($F_{3,66} = 3.429$,

p = .022, η_p^2 = .135). Gaze duration on the image panel was shorter when content was placed at *0.45 m* compared to *1 m* (p = .031) across both interfaces. No effect of trial was observed for gaze duration on image panel ($F_{2,44}$ = .589, p = .559, η_p^2 = .026).

Smartphone Movement. To understand how participants held the phone in the *hybrid* condition, we examined the average smartphone position along the x, y, and z-axes during the task, as shown in Figure 5(b). The x-axis represents horizontal movement (with positive values indicating movement to the right), the y-axis represents vertical movement (with positive values indicating upward movement), and the z-axis represents depth (with positive values indicating forward movement toward the virtual panels). Significant effects of content distance were found on the average z position ($F_{3,69}$ = 4.106, p = .010, η_p^2 = .151), but not on the x ($F_{3,69}$ = 2.298, p = .085, η_p^2 = .091) or y positions ($F_{3,69}$ = .624, p = .602, η_p^2 = .026). Pairwise comparisons revealed that participants held the phone significantly farther away along the z-axis, on average, when the content was placed at *2 m* compared to *0.45 m* (p = .010). We also found effects of trial on phone positions along both the y ($F_{2,46}$ = 7.375, p = .002, η_p^2 = .243), and z-axes ($F_{2,46}$ = 6.215, p = .004, η_p^2 = .213), but not the x-axis ($F_{2,46}$ = .688, p = .507, η_p^2 = .029). For the y position, participants held the phone closer to the origin point in trial 2 (p = .003) and trial 3 (p = .010) compared to trial 1. Similarly, for the z position, participants held the phone closer to the origin point in trial 2 (p = .008) and trial 3 (p = .015) compared to trial 1.

Additionally, we compared the distance the smartphone moved during the task across different distance conditions, when using the *hybrid user interface.* No significant differences were found between the distance levels ($F_{3,69}$ = 1.066, p = .369, η_p^2 = .044). However, there was a significant effect of trial on the distance traveled by the phone ($F_{2,46}$ = 12.801, p < .001, η_p^2 = .358). Participants moved the phone less in trial 2 (p = .004) and trial 3 (p < .001) compared to trial 1.

Head Rotation. We measured head rotation per second during the task for each condition, as shown in Figure 5(c). The analysis revealed a significant effect of the device on head rotation per second ($F_{1,23}$ = 22.660, p < .001, η_p^2 = .496). Head rotation was notably greater in the *hybrid* condition compared to the *HMD-only* condition. We did not find any main effect of content distance ($F_{3,69}$ = .175, p = .913, η_p^2 = .008) or an interaction effect between the two experimental factors on head rotation ($F_{3,69}$ = .217, p = .884, η_p^2 = .009). However, an effect of trial was observed for head rotation ($F_{2,46}$ = 4.953, p = .011, η_p^2 = .177), with significantly less rotation in trial 3 compared to trial 1 (p = .009).

In addition, the range of head movement was analyzed by comparing the minimum and maximum values for each axis across study conditions [83]. Significant effects of interface mode, but not content distance, were observed for most of these values (see Table 4). The statistical results from the omnibus test and post-hoc tests are provided in Appendix B.

4.4 Other Subjective Ratings

Perceived Readability. We found statistically significant main effects for both the interface mode ($F_{1,23}$ = 11.136, p = .003, η_p^2 = .326) and content distance ($F_{3,69}$ = 6.160, p < .001, η_p^2 = .211) (see Figure 4(h)). The *hybrid user interface* demonstrated significantly higher perceived readability compared to using the *HMD only.* Regarding content distance, readability was significantly lower at *0.45 m* compared to *1 m* (p = .023), *2 m* (p = .001), and *5 m* (p = .007). No interaction effects between the independent variables were found for readability ($F_{3,69}$ = 1.837, p = .149, η_p^2 = .074).

Concentration. There was also a significant main effect of interface mode on concentration ($F_{1,23}$ = 6.814, p = .016, η_p^2 = .229) (see Figure 4(i)). The *hybrid* condition exhibited significantly higher concentration levels compared to the *HMD-only* condition across all distance levels. We did not observe any significant main effect of content distance ($F_{3,69}$ = 2.519, p = .065, η_p^2 = .099) or interaction effect between interface mode and content distance ($F_{3,69}$ = .422, p = .738, η_p^2 = .018).

4.5 Qualitative Feedback

After each experimental session, we collected qualitative feedback from participants about their overall experience with both interfaces and how it varied across different content distances. The feedback was segmented into concise statements and organized into related categories using affinity diagramming. These categories were refined through an iterative process, revealing recurring themes summarized below.

Readability and Visual Fatigue. Many participants found text reading easier on the smartphone (P3, P9: *"it was easier to read text on the phone"*; P6: *"easier to use the smartphone when solely focusing on text reading"*; P10: *"reading on the phone felt more natural and easier"*). In contrast, participants noted that reading on the HMD screen was associated with higher visual fatigue (P5: *"reading on the headset was demanding on the eyes"*; P8, P13, P15: *"using only the headset was fatiguing"*; P14: *"using smartphones caused less eye strain during reading"*).

Attention Switching. Unlike reading, participants noted that attention switching was generally easier with the *HMD only* (P2: *"seeing both the image and text through the headset made it easier to switch attention as both panels had the same resolution and color scheme"*; P11, P24: *"easier to switch attention because both panels were at the same distance"*; P13: *"it took less time to switch attention with the HMD only"*; P16: *"using only the headset meant I didn't have to change focal distance"*; P23: *"switching was faster when the text and image panels were aligned at the same angle"*).

In contrast, attention switching was reported as more difficult on the *hybrid* interface (P3: *"When using phones,* [...] *it took some time to readjust focus on the image panel"*; P14: *"it took longer to switch attention on the phone"*). Some explained that the difficulty was more pronounced as the gap between displays grew, requiring more eye movement or arm adjustment. (P18: *"my eyes had to travel greater distances, leading to fatigue"*; P11: *"Due to the depth difference, I had to either refocus my eyes or adjust the position of my arm holding the phone"*; P5, P24: *"I had to hold the phone closer to the AR image, which tired my arms"*; P23: *"as the image moved further, I had to move the phone further away"*).

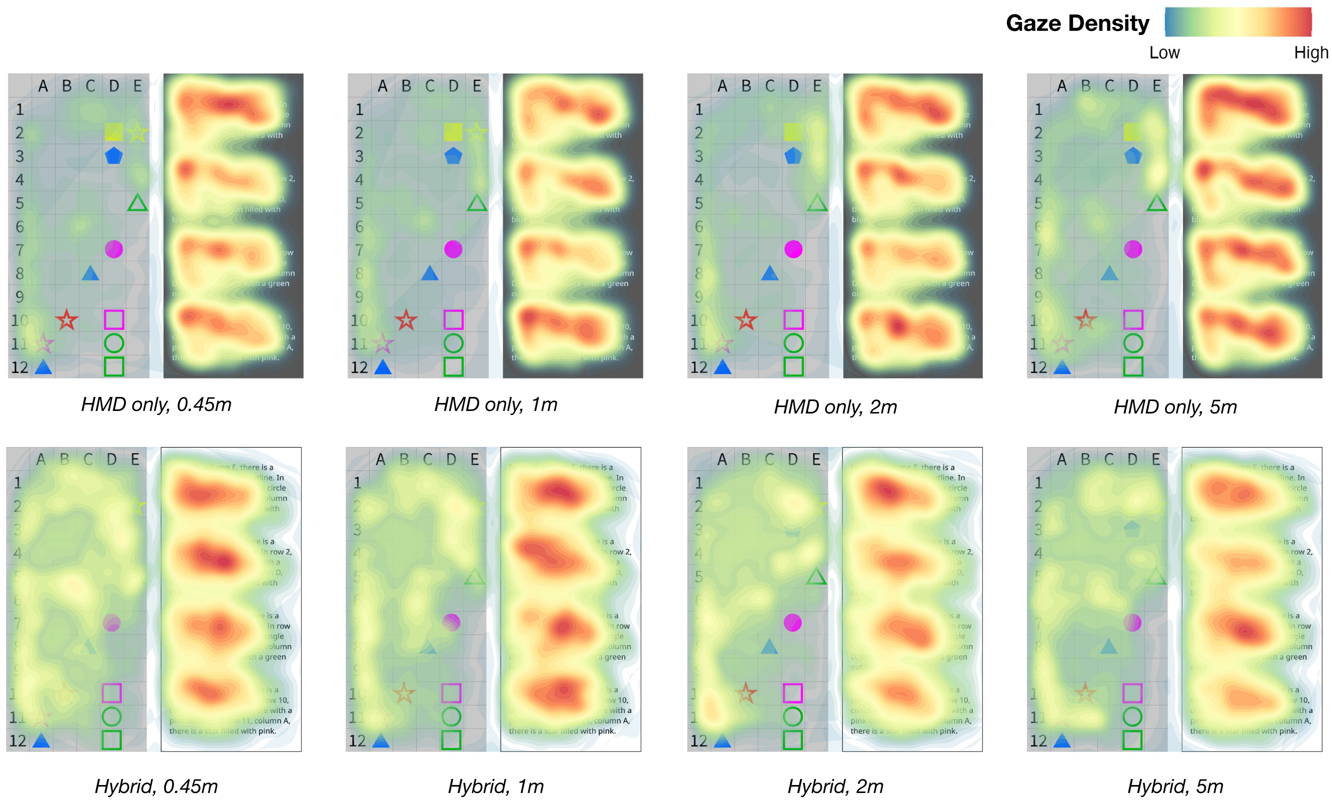


Figure 6: Gaze density maps showing the duration participants focused on each AOI (left: image panel, right: text panel) for each study condition. Gaze samples were aggregated across all participants within each condition.

Distance on Experience of Each Interface. Participants had mixed responses regarding how content distance affected their experience with *hybrid* interfaces. Some found the task more difficult when the image was farther away, citing increased switching costs (P1: *"switching attention was harder with distant images"*; P2: *"easier when content was close"*; P11, P23: *"harder as the image moved further away, requiring more arm adjustment"*; P17: *"difficulty increased as the gap between the panels grew"*; P24: *"greater distance between the image and text made the task harder, forcing more eye movement"*.) However, a few participants found the closest distance more challenging (P6, P14: *"switching attention was uncomfortable at the closest distance; it was hard to focus on the shapes"*.) Others noticed little difference between distance conditions (P4, P7, P12, P13, P18: *"didn't detect much difference"*).

Regarding the *HMD only*, some participants found the task easier when content was placed farther away (P2, P10, P17: *"the task was easier with distant content."* P13, P21: *"close range was more demanding on the eyes and harder for text reading"*). One participant preferred the middle distance (P5: *"I liked the middle range best; close distance was more fatiguing"*). Several others reported no significant difference across distance conditions when using the *HMD only* (P8, P12, P16, P19, P23: *"didn't detect much difference"*; P20: *"the perceived size of panels remained the same, so distance didn't matter much"*)

5 Discussion

In this section, we present the results of our hypothesis testing and highlight the key findings of the study, organized around our original research questions. Based on these findings, we also propose design implications for effectively integrating smartphones into hybrid user interfaces for AR reading tasks.

5.1 Analysis of the Results

RQ1. How does task performance differ between a hybrid user interface and an HMD-only setup across varying virtual content distances? We hypothesized that smartphones, with their higher angular resolution, would provide performance advantages in *hybrid user interfaces* when content is positioned within the intimate distance (**H1-1**). This hypothesis was partially supported. While using *hybrid user interfaces* did not significantly reduce task completion times, it resulted in fewer errors compared to the *HMD-only* setup in the intimate zone. We also expected reduced performance with the *hybrid* setup as the gap between the displays increased, assuming that the cognitive [101] and physical costs [3] of switching—amplified by increased eye movements over these distances—would hinder performance. Specifically, we hypothesized that task performance would either show no significant differences between the interface modes or favor the *HMD-only* setup in spatial zones beyond the intimate zone (**H1-2**). This hypothesis was partially supported. While task completion times showed no significant differences between the interface modes, *hybrid user interfaces* continued to demonstrate lower error rates compared to the *HMD-only* setup, even beyond the intimate distance—contrary to our expectations.

Although task times did not vary significantly across experimental conditions, further analysis of gaze duration on each AOI revealed that participants spent notably less time viewing the text panel when using the *hybrid user interfaces* compared to the *HMD-only* condition, regardless of distance. This result suggests that participants read text faster on the smartphone than on the HMD, which aligns with several participant comments and prior research indicating that physical displays enable faster reading than OST HMDs [87]. However, the AOI analysis also showed that participants spent more time focusing on the image panel when using the *hybrid* condition. Based on participant feedback, we infer that the need to readjust focus to the image panel led to longer gaze durations in this area, offsetting the benefits of faster reading. This may be related to a phenomenon known as *transient focal blur* [3], where information appears temporarily blurry when shifting accommodation to a new focal distance, resulting in longer visual search times. Consequently, the faster text reading on the smartphone did not translate to a shorter overall task completion time for the *hybrid user interface*, even at closer distances.

In terms of task accuracy, the *hybrid* condition outperformed the *HMD-only* condition across all distance levels. We attribute this advantage to the enhanced readability provided by smartphones, as reflected in participant ratings and comments. This improved readability likely contributed to more accurate text reading and overall task performance. Additionally, participants reported higher levels of concentration when using *hybrid user interfaces*, which may further explain the increased accuracy observed in these conditions. This heightened concentration aligns with previous research showing that physical displays enhance focus compared to virtual ones [81]. Notably, task accuracy remained unchanged in the *hybrid* condition even as the gap between displays increased. This consistency likely resulted from participants maintaining a relatively similar viewing distance to the smartphone, regardless of the virtual content's position. Consequently, text readability, and therefore accuracy, remained unaffected.

RQ2. How do perceived workload factors differ between a hybrid user interface and an HMD-only setup across varying virtual content distances? Our hypothesis (**H2-1**), predicting that the *hybrid user interface* would reduce perceived workload factors compared to the *HMD-only* setup in the intimate zone, was partially supported. As expected, using the *hybrid user interface* resulted in lower mental and physical demand when the content was positioned at *0.45 m*. This likely stems from the smartphone's higher angular resolution, reducing both mental effort [65] and physical discomfort [67]. Additionally, consistent with **H2-2**, we observed no significant differences in mental and physical demand, or any other perceived workload factors, between interface modes beyond the intimate zone. We believe that the advantage of *hybrid* condition for mental demand was offset beyond the intimate zone by the mental effort required to integrate information from spatially separated displays [101]. This integration necessitates holding information in working memory while searching for and processing elements from another distant source, thereby increasing cognitive load. Similarly, the benefits of the *hybrid* condition regarding physical demand were also negated. We suspect that this effect was due to the increased arm fatigue in the *hybrid* condition at greater distances, rather than the increased visual fatigue we initially hypothesized.

Contrary to our expectations, visual fatigue did not increase with larger panel gaps in *hybrid user interfaces*. Instead, participants reported the highest visual fatigue at *0.45 m* in both interface modes. We attribute this to the vergence-accommodation conflict [33] and the blurriness of content [70] that occurs when virtual content is presented at close distances on the HMD. Since the HoloLens 2 has a fixed focal plane set at 2 m [70], the mismatch between accommodation and vergence cues would have been especially pronounced when content was at *0.45 m* [57], leading to considerable eye strain. Even in the *hybrid* condition, where text was read on the smartphone, viewing HMD-presented images likely induced the same adverse effects, leading to elevated visual fatigue compared to other distances. Moreover, while eye rotation may have decreased when the virtual image panel was near the smartphone (i.e., at *0.45 m*), the HMD's fixed focal distance meant accommodation demands remained constant across all distance conditions. Consequently, even at *0.45 m*, there was still a significant demand for the eyes to accommodate between different depths in the *hybrid* condition.

Furthermore, visual fatigue was consistently higher with the *HMD-only* setup compared to the *hybrid user interface* across all distances to the virtual content. This increased fatigue in the *HMD-only* condition can likely be attributed to several factors. First, participants may have experienced greater eye strain from performing visually demanding tasks on a lower-resolution display [112]. Second, the stereoscopic viewing of both image and text may have contributed this fatigue, as challenges associated with stereoscopic displays—such as shifting demands on accommodation-vergence linkage, insufficient depth information, and unnatural blur—are known to cause visual discomfort [59]. Visual fatigue is a significant concern for AR tasks conducted for extended periods, as prolonged visual fatigue can make these displays impractical for use [33]. This issue is highlighted by a previous study [97], in which participants were forced to stop a two-hour long industrial AR task due to "pressure in the eyes."

In contrast to visual fatigue, greater arm fatigue was reported with the *hybrid user interface* across all distances. Additionally, there was increased arm fatigue when viewing content at distances of *2 m* and *5 m* compared to *0.45 m* in the *hybrid* condition. Analysis of the average phone positions showed that this increased fatigue resulted from participants extending their arms to hold the phone closer to the content when it was positioned farther away. According to their feedback, this was an attempt to reduce the extra effort required to rotate the eyes over large distances. In summary, while greater distance switching between virtual and physical displays in *hybrid user interfaces* doesn't necessarily lead to increased visual fatigue, it does result in more arm fatigue in AR reading tasks.

RQ3. How do users' viewing behaviors differ between a hybrid user interface and an HMD-only setup across varying virtual content distances? Finally, our hypothesis (**H3**) predicting an interaction effect between interface mode and content distance on viewing behaviors was partially supported. We anticipated that participants would adopt distinct behaviors to manage the challenges of switching attention between displays when using *hybrid user interfaces* for distant content. Analyses of visual attention and smartphone-holding positions confirmed this assumption, revealing an interaction effect in both measures.

Regarding visual attention, the *hybrid user interface* led to significantly less frequent eye shifts between text and image panels compared to the *HMD-only* setup at the *2 m* distance. No such difference was observed at other distances. This suggests that at *2 m*, switching attention between the panels was more challenging with the *hybrid* condition, prompting participants to rely more on memory rather than repeatedly revisiting the panels [14]. In contrast, the more frequent attention shifts in the *HMD-only* condition at *2 m* can be seen as *cognitive offloading* [92]—using physical actions to alleviate the cognitive demands of a task. By frequently shifting their gaze, participants likely externalized their mental processes, reducing the cognitive effort required to remember information [14]. Additionally, participants using the *hybrid user interface* at this distance were observed holding the smartphone further towards the image panel on the HMD compared when content was positioned at *0.45 m*. This adjustment likely aimed to facilitate easier visual switching between displays.

In terms of head rotation, no interaction effect between the experimental factors was observed. However, a significant main effect of the interface mode was identified. Participants demonstrated more head rotations in the *hybrid* condition compared to the *HMD-only* condition across all content distances. A detailed analysis of head movements revealed that when using the *hybrid user interface*, participants tended to lower their heads more along the pitch axis and exhibited a wider range of motion along both the yaw and roll axes. This is expected, as smartphones are typically held below eye level, requiring a head flexion of approximately 33–45 degrees [98]. These findings indicate that head rotation represents an additional physical cost associated with display switching. Notably, unlike other metrics, participants did not display any behaviors that suggested efforts to mitigate these costs.

5.2 Design Implications

Based on our analysis, we have identified five key design considerations for effectively integrating smartphones into hybrid user interfaces for AR reading tasks, as illustrated in Figure 1. These insights not only address current challenges but also lay the groundwork for more efficient hybrid interactions in the future.

D1. Use smartphones to display text for reading-intensive AR tasks. Our findings suggest that hybrid user interfaces are generally more effective than using HMDs alone for achieving better text readability. Using smartphones for reading text improves perceived readability, reduces reading time, and enhances concentration, leading to more accurate reading performance. Additionally, it alleviates visual fatigue, which is crucial for prolonged reading tasks. Therefore, we recommend using smartphones as supplementary displays for AR tasks that primarily focuses on reading.

D2. Adaptively position virtual content on HMDs when smartphones are used as supplementary displays. While smartphones can enhance AR reading tasks when used at close distances, significant gaps between the virtual display and the smartphone may prompt users to adopt compensatory behaviors to manage the challenges of display switching. To mitigate these challenges, virtual panels should be adaptively positioned to remain within the user's intimate distance, provided this placement does not interfere with the AR task.

D3. For less intensive AR reading tasks, use smartphones as supplementary displays for text when the virtual content is within an intimate distance. In this context, smartphones are particularly effective for reading text, as they help reduce both mental and physical load. This setup could be utilized in educational settings, allowing students to closely examine and manipulate 3D anatomical models while simultaneously accessing related information on their smartphones.

D4. Avoid using smartphones as displays when virtual content is positioned beyond beyond the social distance. As the distance between the virtual content on the HMD and the smartphone display increases, the readability benefits of smartphones diminish due to compensatory behaviors users adopt to deal with high display switching costs. In such situations, we recommend using smartphones primarily as input devices—for example, to select and manipulate virtual objects using the phone's spatial pose and touchscreen [61, 74]—rather than as display devices.

D5. Avoid placing text within the intimate distance on the HMD when smartphone use is impractical. In scenarios where smartphone use is not feasible, such as when the user's hands are occupied (e.g. assembling a model), text content should be positioned further away than the intimate distance on the HMD. While the optimal distance for placing content on devices like the HoloLens2 is approximately 2 meters [70], this might not always be achievable depending on the specific user scenario. In these cases, we recommend against placing text too close, as it can cause significant visual fatigue and poor readability.

6 Limitations and Future Work

Our study has several limitations that warrant further exploration.

First, our focus on investigating the effectiveness of using smartphones as supplementary displays introduced some inconsistencies between experimental conditions. For example, the distance between text and image panels varied across the *hybrid user interface* and *HMD-only* setups. While this reflects the different panel positioning available in different interface modes, it makes it challenging to isolate the effects of display type from those of panel gaps. Additionally, there may be few instances where a virtual text label would be within arm's reach on the HMD instead of beside the referent (e.g., handheld text panels), limiting the generalizability of our findings. Including an intermediate condition—where text and image panels are on the HMD but with the text panel positioned at arm's reach—would have helped disentangle these factors. We acknowledge the absence of such a condition as a significant limitation of our study.

Similarly, the text and background colors differed across display conditions as we optimized the visual style for each display type. This design decision was made to ensure a fairer evaluation, as using a uniform color scheme (e.g., universally applying dark or light mode) would have disadvantaged one condition over the other. However, this variation in color modes may have also introduced bias, making it uncertain whether the observed effects were driven by the displays themselves or influenced by the differences in color. Therefore, our findings are preliminary and further research is needed to fully understand the effect of using smartphone displays for text reading.

Additionally, to fully understand the benefits and drawbacks of hybrid user interfaces, their long-term effects need to be explored. Although not the primary focus of our study, we observed notable changes in participants' viewing behaviors over the course of trials. These included shifts in visual attention, changes in smartphone-holding postures, and a decrease in head rotations as the trials progressed. Such behavioral adaptations could influence both performance and subjective experience over time, though the extent of these effects remains unclear. Furthermore, the long-term impact of conflicting factors—such as improved visual comfort alongside increased arm fatigue—observed with the hybrid user interface requires further exploration and presents a valuable opportunity for future research.

Finally, some of our findings may be specific to the particular task design used in this study. In an effort to create a realistic AR reading scenario, we designed a task that involved both text reading and frequent context switching between textual content and other virtual elements. While this setup mimics an AR reading environment, it is important to acknowledge that reading in AR can take many forms and occur in various contexts. Factors such as the intensity of text reading, the frequency of context switching, and the cognitive demands of the task may all influence the user experience with hybrid user interfaces. Therefore, future research should explore a wider range of AR reading tasks to better understand the effectiveness of hybrid user interfaces across different use cases.

7 Conclusion

In this work, we investigated the impact of hybrid user interfaces on AR reading tasks across different virtual content distances to examine the trade-offs between improved legibility and visual switching costs when combining OST HMDs with smartphone displays. We conducted a within-subject experiment with 24 participants, exploring the interaction effects between interface mode and content distance on task performance, perceived workload, fatigue, and viewing behavior. The results indicate that while the legibility benefits of hybrid interfaces outweigh the costs of display switching at close distances, this advantage diminishes as the gap between the AR content and the smartphone display increases. As users adopt compensatory behaviors to manage the growing switching costs, the effectiveness of hybrid interfaces declines. Our findings offer valuable insights for optimizing smartphone integration in hybrid user interfaces, contributing to the development of more effective AR systems for reading applications. Additionally, our research sheds light on the benefits and drawbacks of combining smartphones with HMDs, which can inform the design and development of future hybrid user interfaces.

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A Questionnaires for User Study

This appendix details the questionnaires used in our study.

Table 2: Mid-experiment questionnaires given after each experimental condition.

Category	Measure	Question	Scale
Perceived workload	Mental demand	How mentally demanding was the task?	0 (*very low* or *perfect*) to 100 (*very high* or *failure*)
	Physical demand	How physically demanding was the task?	
	Performance	How successful were you in accomplishing what you were asked to do?	
	Effort	How hard did you have to work to accomplish your level of performance?	
	Frustration	How insecure, discouraged, irritated, stressed, and annoyed were you	
Fatigue	Visual fatigue	Please rate the condition of your eyes.	1 (*very rested*) to 7 (*very fatigued*)
	Arm fatigue	Please rate the condition of your arms.	
Additional subjective ratings	Perceived readability	I could easily read the information on the display.	1 (*strongly disagree*) to 7 (*strongly agree*)
	Concentration	I found it easy to concentrate on the task.	

Table 3: Post-experiment questions answered with short responses.

Question
1. How did your experience performing the task differ when using the AR headset alone versus using the AR headset in combination with the smartphone?
2. Did your experience using the AR headset with smartphone vary depending on the distance of the augmented panel? If so, how did it differ?
3. Did your experience using the AR headset alone vary depending on the distance of the augmented panel? If so, how did it differ?
4. Please share any additional feedback you have regarding the study.

B Statistical Results on the Range of Head Movement

This appendix presents supplementary statistical findings related to section 4.3, "Head Rotation."

Table 4: Omnibus test results for the range of head motion. Rows highlighted in grey indicate statistically significant results. Asterisks denote the significance level of each effect ($^*p$ < .05, $^{**}p$ < .01, $^{***}p$ < .001).

	Interface Mode			Content Distance			Interface Mode × Content Distance		
Variable	$F_{1,23}$	p	η_p^2	$F_{3,69}$	p	η_p^2	$F_{3,69}$	p	η_p^2
Min(x)	19.694	$< .001^{***}$	.461	3.494	$.020^{*}$	.132	.038	.99	.002
Max(x)	25.596	$< .001^{***}$	.527	2.527	.065	.099	.644	.589	.027
Min(y)	32.540	$< .001^{***}$	.586	.668	.575	.028	.631	.598	.027
Max(y)	1.009	.325	.042	1.355	.264	.056	.262	.853	.011
Min(z)	21.661	$< .001^{***}$	.485	1.403	.249	.058	.717	.545	.03
Max(z)	25.596	$< .001^{***}$	.527	2.527	.065	.099	.644	.589	.027

Table 5: Results of post-hoc pairwise comparisons between interface modes for the range of head motion. Rows highlighted in grey indicate statistically significant results. Asterisks denote the significance level of each effect ($^*p$ < .05, $^{**}p$ < .01, $^{***}p$ < .001).

Variable	Comparison	$t(23)$	p
Min(x)	*HMD only* ↔ *Hybrid*	-4.438	$< .001^{***}$
Max(x)	*HMD only* ↔ *Hybrid*	-5.059	$< .001^{***}$
Min(y)	*HMD only* ↔ *Hybrid*	5.704	$< .001^{***}$
Min(z)	*HMD only* ↔ *Hybrid*	4.654	$< .001^{***}$
Max(z)	*HMD only* ↔ *Hybrid*	-5.059	$< .001^{***}$

Table 6: Results of post-hoc pairwise comparisons between content distances for the range of head motion. Rows highlighted in grey indicate statistically significant results. Asterisks denote the significance level of each effect ($^*p$ < .05, $^{**}p$ < .01, $^{***}p$ < .001).

Variable	Comparison	$t(69)$	p
Min(x)	*0.45m* ↔ *1m*	-1.945	.335
	0.45m ↔ *2m*	-3.212	$.012^{*}$
	0.45m ↔ *5m*	-1.815	.444
	1m ↔ *2m*	-1.267	1
	1m ↔ *5m*	0.130	1
	2m ↔ *5m*	1.397	1