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Information Access Costs With an Augmented Reality Head-Mounted Display

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Abstract

Objective: This work examined performance costs for a spatial integration task when two sources of information were presented at increasing eccentricities with an augmented-reality (AR) head-mounted display (HMD).
Background: Several studies have noted that different types of tasks have varying costs associated with the spatial proximity of information that requires mental integration. Additionally, prior work has found a relatively negligible role of head movements associated with performance costs. However, currently no studies have examined the magnitude of costs for spatial integration tasks when information is separated laterally using an AR-HMD.
Methods: Participants completed a spatial integration task in which information to be integrated was separated by multiple lateral visual angles. Participants were required to judge whether XY coordinate numbers were located within a designated red zone presented on a map.
Results: A significant effect of separation distance was found on response time, with no impact on accuracy. The effect of separation on response time increased considerably in the AR-HMD format compared to prior work examining the performance costs on a wide-angle monitor. Head movements became more costly to response time once information began to enter the head field at around 32 degrees of separation.
Conclusions: The current results taken with previous work indicate a task-device interaction, in which head movements become more costly dependent upon the type of information to be integrated.
Application: Our findings imply the need for careful evaluation of task characteristics when modeling information separation costs on a desktop display for an AR-HMD format.

Keywords

information access effort, proximity-compatibility principle, attentional processes, augmented reality head-mounted display, display layout, working memory

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Introduction

Advanced displays, such as augmented-reality (AR) head-mounted displays (HMDs), are increasingly changing how people interact with multiple layers of information by superimposing virtual content onto the real-world. Many studies have demonstrated the benefits of HMDs in real-world tasks (Dey et al., 2018; Jeffri & Rambli, 2021), such as education (Fonseca et al., 2014), manufacturing (Lamberti et al., 2014), and health care (Ameri et al., 2019). While AR-HMDs have shown benefits in these real-life tasks, their potential is particularly important in high-stakes situations where split-second decisions can have critical implications. The use of AR-HMDs in military contexts has become an important area of focus regarding support for service members on the battlefield. Military operations often require service members to integrate and rapidly respond to multiple sources of information. Consider a scenario where service members are patrolling an urban area, and the leader receives drone footage or map updates of hostiles entering a building nearby presented on their HMD. Simultaneously, intelligence updates are received in a chat box also displayed on their HMD. Based on these sources of information, a decision must be made of whether or how to approach and engage. In this scenario, both channels of information can be displayed in many ways, but significant costs may arise if display designs fail to balance support for allocating attention efficiently, between domains and on the display. Safety and time-critical tasks like these have led to the growing interest in the display design of AR-HMDs to support users in complex and dynamic situations.

When designing displays, such as head-up displays (HUDs) in vehicles or AR-HMDs, there is a tendency to place relevant information directly in front of user’s line of sight to facilitate easy access. Prior meta-analyses have highlighted performance benefits of HUDs and HMDs compared to a head-down display (HDD), such as a smartphone or an in-cockpit dashboard display (Fadden et al., 2000, 2001; Warden et al., 2024). However, challenges of directly superimposing information can arise when users must process information presented on the display (i.e., the near domain) of an AR-HMD and information in their real-world surroundings (i.e., the far domain) beyond the display. Directly overlaying information creates visual clutter, which can hinder the user’s ability to process both domains effectively and efficiently (Warden et al., 2024; Wickens & Alexander, 2009; Wickens et al., 2022). For example, in the earlier scenario, a service member’s AR-HMD might overlay drone footage or a map and chat box updates in their field-of-view (FOV). While this provides immediate access to multiple sources of information, excessive display clutter may obscure other critical information in the real-world, such as detecting a threat.

One method for mitigating the costs of display clutter created by overlaying multiple sources of virtual content onto the real-world is to spatially separate information, either via a head-down display (e.g., tablet) or, in the context of an AR-HMD, by positioning the content out of the users forward line of sight. However, such spatial separation can impose greater information access effort (IAE) in the form of increased scanning or head movement requirements. IAE refers to the level of physiological or cognitive effort required to access information (Wickens, 2014). Information easily accessed with eye movements alone falls within the eye field (approximately 20–25° of spatial separation; Houtmans & Sanders, 1984). Beyond this separation, the head field is entered, where a neck rotation becomes necessary to access information up to around 60°. At further distances, a body movement may be initiated to reduce joint loading on the head and neck (Kim et al., 2010). Whether displays should be overlaid or presented separately, and if the latter, how far, is dependent on tradeoffs associated with the type of task involved.

The costs of positioning information at progressively wider angles of separation in the visual field, referred to as the visual angle of separation or VAS, has been examined in a number of investigations, both outside the lab (Ballard et al., 1995; Draschkow et al., 2021; Martin-Emerson & Wickens, 1992; Schons & Wickens, 1993; Yang et al., 2014), and within (Poole et al., 2023; Warden et al., 2024). More specifically, Warden et al. (2022, 2024) examined VAS at four levels ranging from 2 to 40° on a flat-panel display, and 2–50° with an AR-HMD, using two different types of attentional tasks: one requiring focused attention, and the other requiring arithmetic integration of information between two separate locations with binary (yes/no) response options. The latter imposed greater working memory demands, as greater VAS requires retaining information until the second source enters foveal vision, raising performance costs unless mitigated by a strategy (Wickens & Carswell, 1995).

In their arithmetic integration task, Warden et al. found only small effects of increasing VAS. Head movements rose slightly at higher VAS (about 0.07 movements per degree), without impairing response time or accuracy across display types. These findings suggest the task's low working memory demands minimally interfered with processing the spatially separated information. Investigating how this changes with a more visually complex integration task was a key motivation behind Poole et al. (2023) and the present study.

A study conducted by Poole et al. (2023) on a flat panel display, extended VAS out to 128°, to ensure that ample head movements were required. This study also examined a far more complex spatial integration task in which participants were required to compare the position of a 6-digit XY coordinate set presented on one side of the display, with a location on a spatially separated map presented on the other side at varying visual angles of separation, to determine if that location was inside or outside of a red zone depicted on the map. This task was identical to that employed in the current experiment. However, then it was presented on a wide-angle desktop display. Here, it was on an HMD as described below. Poole et al. (2023) reported response times more than twice those in Warden et al. (2024), who used a much simpler information-integration task on a flat panel display. In Poole et al., RT increased modestly with VAS at around 11 ms/degree. RT was not correlated with head-movement rate, which increased by around 0.07 movements per degree and plateaued at around 64°. In neither of the above studies did error rate increase with VAS.

The current study replicated the methods and used participants drawn from the same undergraduate participant pool as the study of both Poole et al. (2023) and Warden et al. (2024); but in the current study, information was presented to participants on a light-weight HMD. This distinction matters because the HMD format may increase encoding time, slow head movements due to weight and balance, or cause participants to avoid head movements, relying more on imperfect memory (Ballard et al., 1995), thereby sacrificing accuracy.

We hypothesized the following:

- **H1:** The cost of increasing separation, assessed by response time, will exceed the cost observed by Poole et al. (2023) as a consequence of the presentation of information in an HMD platform.
- **H2:** The increase in head movement frequency at larger VAS will be significantly correlated with longer RTs.
- **H3:** We anticipate a speed-accuracy tradeoff similar to that observed by Poole et al. (2023), such that the increased number of head movements and response time at larger visual angles will preserve constant accuracy across all eccentricities.

Method

Participants

Twenty-eight students enrolled in an introductory psychology course at Colorado State University received course credit for completing the experiment. The sample size of 28 aligns with previous studies examining spatial separation and task performance using HMDs, finding sufficient power to detect medium effect sizes with 24–26 participants (Warden et al., 2024). Participants had self-reported normal or corrected vision and passed an electronic Ishihara color blindness test. The study was approved by the university's IRB, and all participants gave informed consent prior to the experiment.

Stimuli and Apparatus

All stimuli were presented on a Microsoft HoloLens 2 (HL2) AR-HMD, a mixed-reality display that merges virtual information with the real-world. The experiment was developed in Unity using version 2022.1.10f1. Eight map images were created using an online terrain generator Caltopo (Caltopo, nd). These maps were edited in Adobe Photoshop to include thicker grid lines than those used in Poole et al. (2023) to ensure visibility when presented with the HL2. Maps were 1149 by 1149 pixels and consisted of a desert terrain background, eight evenly separated horizontal and vertical grid lines, grid line numbers ranging from 10–49, and a designated red zone. See Figures 1 and 2 for examples of stimulus materials.

The border of the red zone varied in complexity, consisting of either 3, 7, or 10 lines with vertices that were either greater than 90° or curved. The red zone also varied in spatial location between maps; for an example of the location differences of the red zone see Figure 1. Coordinate locations varied in difficulty ranging from low to high uncertainty based on their distance from the designated red zone line. Coordinate numbers could never be directly on the zone line. The center of the map image was placed to the left or right of the participants forward line of sight. The center of the grid coordinate numbers was presented on the opposite side of the map and displaced by one of four degrees of separation (16, 32, 64, 128° of spatial separation). For example, if the map was positioned on the left side relative to the participants forward line of sight, then the grid coordinate number was displayed at one of these four degrees of separation to the right of the map. Map coordinates consisted of 6 numbers and were utilized in a similar way as the standard Military Grid Reference System but were modified to include a comma separation between the horizontal and vertical grid axis values and a decimal point between the second and third horizontal or vertical coordinate value. This modification was to allow for an easier distinction between horizontal and vertical grid coordinates. All participants were seated 3 feet in front of a white wall to minimize external clutter, and the virtual content within the display was presented 23.6 inches from the participant.

Task

Participants completed a spatial integration task requiring spatial estimation of the location of map coordinates (see Figure 1). The spatial integration task required participants to read grid coordinate numbers and find the location of those coordinates on the map, to assess whether the grid coordinate number was located inside of the designated red zone. At the start of the trial, participants focused on a fixation cross that appeared at either the left or right of their forward line of sight. Once they fixated on the cross, they pressed the “spacebar” on a Bluetooth keyboard to start the trial. A map immediately replaced the fixation cross and grid coordinate numbers appeared to either the left or right of the map. Participants were instructed to respond to whether the grid coordinate numbers were located inside of the designated red zone. Participants responded with both hands providing a “caps lock” keypress for yes if the given coordinate was located in the red zone, and an “enter” keypress if it was not.

Experimental Design

The experiment was a 4 (spatial separation distances 16, 32, 64, and 128°) condition within-subjects design. Participants completed two counterbalanced map presentation blocks in which the map appeared consistently to either the left or right of the participants forward line of sight, to minimize order effects. When the map was presented to the right, the coordinate numbers appeared to the left. Conversely, when the map appeared to the left, the coordinate numbers appeared to the right. Prior to the start of each block participants completed 8 practice trials (2 per separation distance) for a total of 16 practices trials during the experiment. This ensured participants knew where to find the coordinate locations on the map. Participants received feedback during practice trials: a ding for correct responses and a buzzer for incorrect ones. If incorrect, the research assistant asked whether help was needed and provided guidance on subsequent trials until the participant clearly understood the task. Within each block there were 4 counterbalanced spatial separation subblocks in which the center of the maps and grid coordinate numbers were separated by one of four visual angles of separation (16, 32, 64, or 128°). Separation subblocks contained a different map, different red zone line contours and different grid reference numbers or number locations from other subblocks. Trials within each separation subblock were randomized. For each separation subblock, participants completed 25 trials, which included one attention check trial consisting of coordinates positioned in a corner distant from the red zone. Participants were instructed to respond as accurately and quickly as possible. They were given the option to take a 60-s break between each display separation subblock.

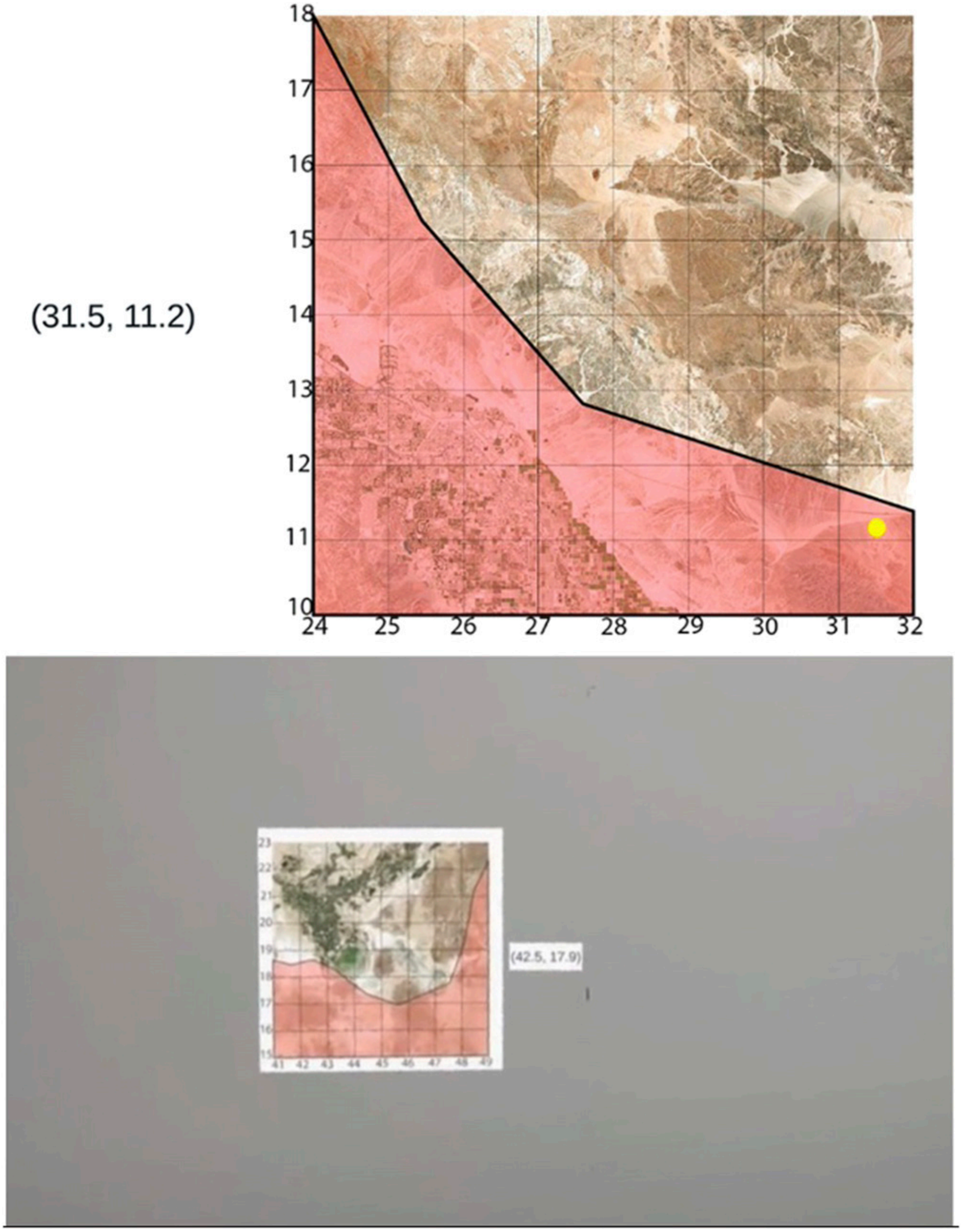

Figure 1. The top image shows an illustration of a single trial for the spatial integration task with the XY coordinates positioned to the left of the map. The yellow dot represents the location of the grid coordinate and was not present in the experiment; participants were forced to estimate approximate location from the given coordinates. The bottom image shows an example of how the stimuli appeared with the AR-HMD during the experiment, with the coordinates positioned to the right of the map. Both examples show the center of the map and grid coordinates positioned 16° apart.

Procedure

All participants gave informed consent to participate in the experiment. Before the experiment, participants were trained on how to determine locations using a map with 6-digit grid coordinates. Participants' eyes were calibrated to the HL2 prior to the start of the experiment. Participants sat in a stationary chair to complete the experiment. The experiment lasted approximately 1 hour.

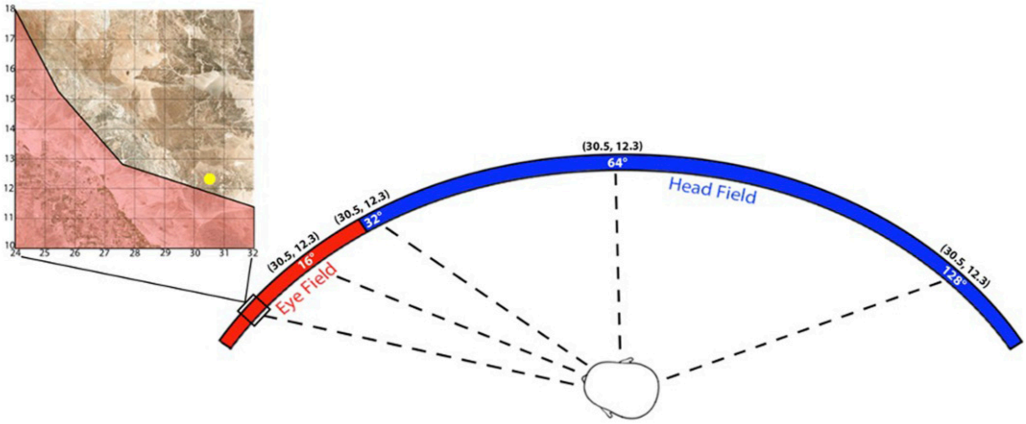

Figure 2. The image shows an illustration of where information could be presented around the user with the box representing the map and the coordinates representing their virtual location at each separation distance. The red eye field represents approximately 32° of separation, with the head and body fields in blue beyond this distance. The yellow dot was not present in the experiment.

Results

Prior to analysis practice trials were excluded from the data. One participant had chance accuracy (51%) and was removed from the data. Additionally, a total of 443 outlier trials out of 5400 total trials (8%) were removed from the data for the following reasons. Due to limitations in recording head movements with the HL2 AR-HMD, the final trial of the experiment was deemed an outlier trial and, therefore, excluded from the analysis (a total of 27 trials were removed). Additionally, there were instances at 64° and 128° of separation where we could readily identify that head movement data was not properly recorded: when participants made a correct response but zero head movements (63 trials) or only a single head movement (91 trials) was recorded, rather than the required two head movements needed to complete the task at these large angles, resulting in the removal of 154 trials. After these outliers were removed, further outlier criteria were set a priori based on a response time below 300 milliseconds or above 1.5 times the upper bound of the interquartile range (262 trials), the same as in Poole et al. (2023). The lower bound criteria is based on physiological and psychological limitations by which a person could reasonably cognitively process and respond to the current complex integration task. Given the multi-step nature of the current task (possible head movements, encoding 6-digits, determining their location on a map at a separate location, and a motor response) we determined responses below 300 ms were likely anticipation, or accidental, rather than valid task engagement. This is supported by our average response time for the task at each VAS being far higher than our lower bound outlier criteria. Response time data were log transformed to correct for the positively skewed distribution. To aid in visual comprehension, nontransformed response times are plotted in Figure 4. Note that the same pattern of results emerged with accuracy and response time without removing the head movement outliers; however, the correlations between head movements and response time differed slightly. Given these similar results we opted to report results from the accuracy and response time data with the head movement outliers removed.

Data analyses were conducted using separate one-way repeated measures ANOVAs to test the effect of increasing spatial separation on performance. All data were analyzed in R Studio. Response time was recorded from the start of the trial after participants pressed the “space” bar to reveal the map until they responded. Responding “yes” when the coordinate was in the red zone or “no” when it was outside of the designated red zone was recorded as a correct response. To establish minimum head movement thresholds, we simulated trials at each spatial separation distance so that the AR-HMD device recorded the head movement displacement for each separation.

Effect of Spatial Separation on Performance

Accuracy. Mean accuracy data are presented in Figure 3.

Average accuracy was found to be high across all separation distances (approximately 92%). A one-way repeated measures ANOVA revealed no statistically significant effect of separation on accuracy, $F\ (3, 78) = 2.03$, $p = .12$, generalized $\eta^2 = 0.01$. Increasing information spatial separation did not impose a cost to accuracy.

Response Time. Mean response time data are shown in Figure 4.

A one-way repeated measures ANOVA revealed a statistically significant main effect of display separation on response time, $F\ (3, 78) = 45.70$, $p < .01$, generalized $\eta^2 = 0.20$, indicating that response time increased by 1.6 s, 7.57–9.18 s, as display separation increased. Paired t-tests revealed no statistically significant effect between the 16° and 32° of separation, $t\,(26) = 0.03$, $p = .98$, $d = 0.00$. However, there were statistically significant effects between 32° and 64° ($t\,(26) = 5.17$, $p < .01$, $d = 0.56$), and between 64° to 128° ($t\ (26) = 4.16$, $p < .01$, $d = 0.56$), showing a fairly linear increase in response time across the greater separation distances.

Effect of Separation on Head Movements

Mean head movement data are shown in Figure 5.

A one-way repeated measures ANOVA revealed a statistically significant effect of visual angle of separation on average head movements ($F\ (1.87, 48.59) = 404.42$, $p < .01$, generalized $\eta 2 = 0.90$). Paired t-tests showed no difference between 16° and 32° of separation ($t\ (26) = 0.51$, $p = .62$, $d = 0.09$). However, when the visual angle of the coordinates location exceeded the lateral FOV of the device (43°) from 32° to 64° of separation, head movements drastically increased as expected ($t\ (26) = 23.14$, $p < .01$, $d = 4.41$), stabilizing between 64- and 128-degrees ($t\ (26) = 1.15$, $p = .26$, $d = 0.19$), showing that head movement frequency did not increase across the larger spatial separation.

Effect of Head Movements on Performance

A scatter plot of mean head movement and response time data for 32°, 64°, and 128° separation distances are shown in Figure 6.

For all display separations, the number of head movements was not significantly correlated with accuracy decrements ($p > .22$). However, for RT at 32° of separation, average head movement

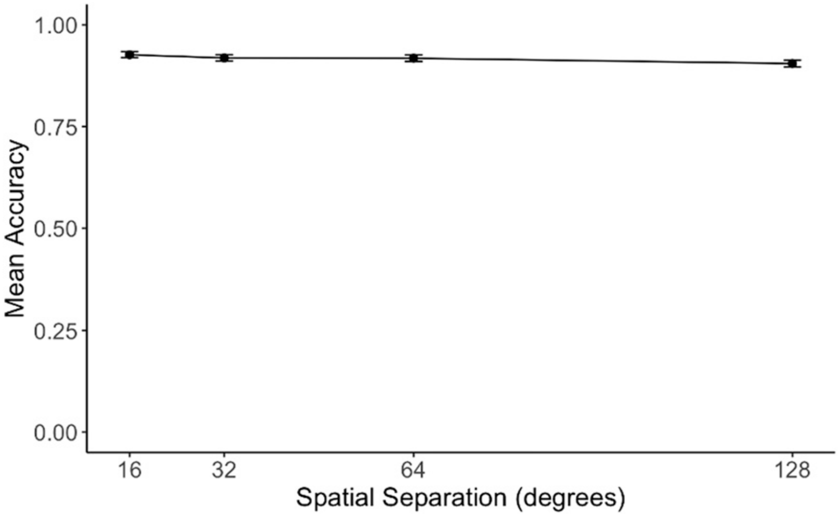

Figure 3. Mean accuracy plotted as a function of display separation (measured as degrees of spatial separation). Error bars represent one standard error from the mean.

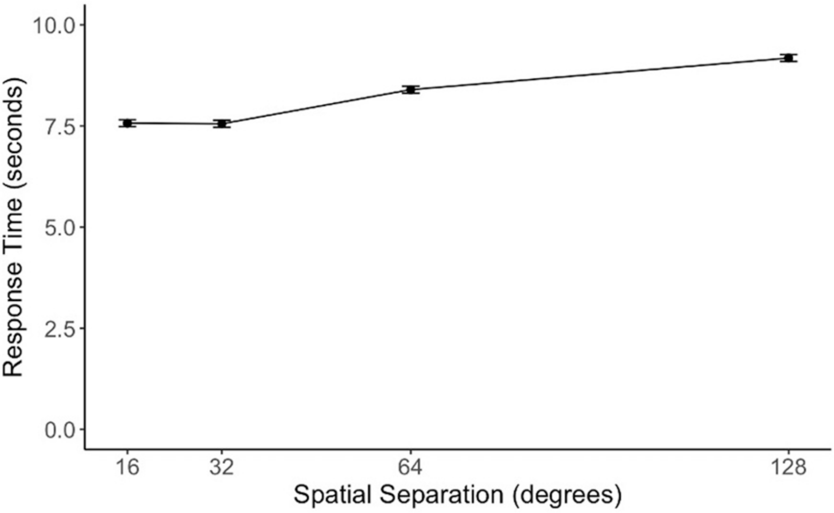

Figure 4. Mean response time (measured in seconds) plotted as a function of display separation (measured as degrees of spatial separation). Error bars represent one standard error from the mean.

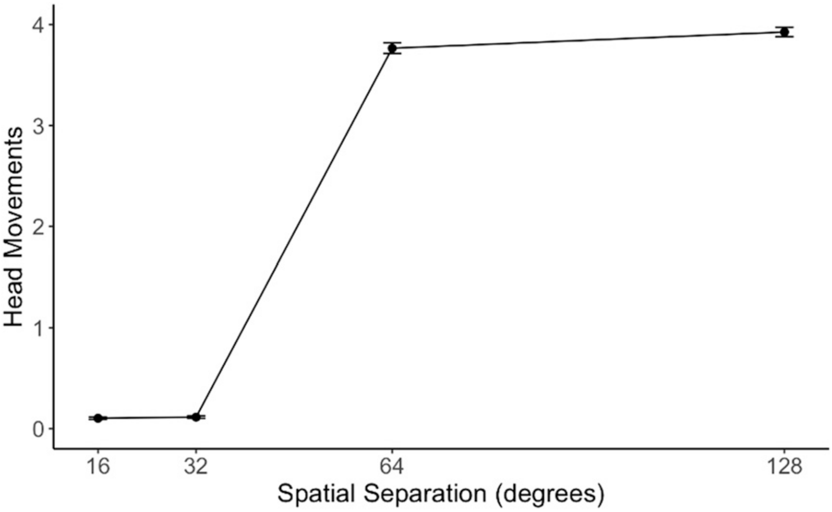

Figure 5. Mean number of head movements per trial plotted as a function of display separation (measured as degrees of spatial separation). Error bars represent one standard error from the mean.

frequency was significantly moderately correlated with longer average response times (t (25) = 2.52, $p = .02$, $r = 0.45$). Similarly, moderate correlations between average response time and head movement frequency were found statistically significant at 128° of separation (t (25) = 2.12, $p = .04$, $r = 0.39$). The correlation between average response time and head movement frequency was not statistically significant but was approaching conventional levels of significance at 64° (t (25) = 1.95, $p = .06$, $r = 0.36$). In short, at the three larger separations there was a relatively weak tendency for those who made more head movements to require more time to complete the task.

Discussion

The current experiment examined performance costs associated with increased spatial separation between two sources of information required for a

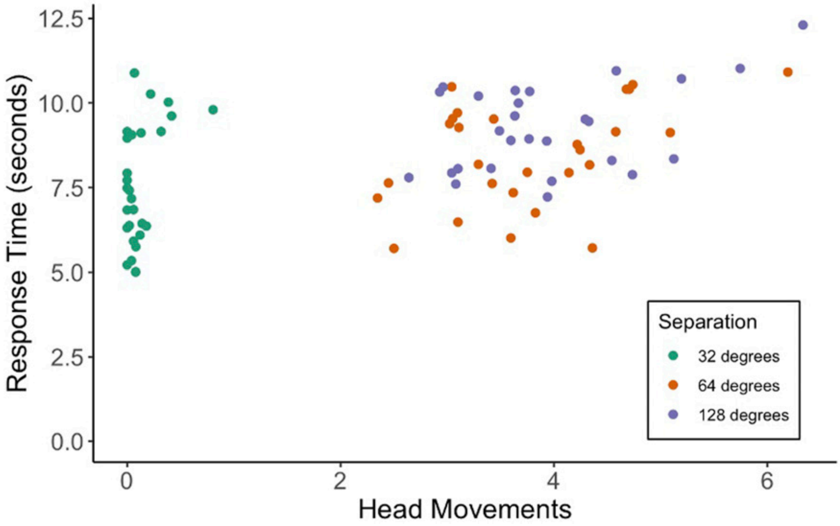

Figure 6. Scatterplot of mean head movements per trial plotted as a function of response time for 32°, 64°, and 128° of separation.

spatial integration task presented with an AR-HMD. Given the increasing prevalence of these devices in safety-critical domains, quantifying IAE costs is important to inform design guidelines for how to best present information for various tasks, particularly complex spatial integration tasks. Additionally, this study builds upon previous work which found a linear increase in response time at increasing eccentricities (ranging from 16° to 128° of separation), along with a nonlinear increase in head movements that leveled off between 64° and 128° (Poole et al., 2023). Consistent with findings from Warden et al. (2022, 2024), Poole et al. (2023) found on a wide-angle flat panel display that for the spatial integration task, head movements did not impose costs to either RT or accuracy performance at any VAS out to 128°. The current work examines whether these findings, using an identical task, procedures and participant characteristics, also extend to or are amplified in an AR-HMD format, where, as with any HMD, presented information, and thus performance, may be impacted by movement, display jitter, weight, and inertia (Lutwak et al., 2023; Regan & Miller, 2017; Warden et al., 2024).

Our hypothesis that VAS effects on performance would be enhanced when compared to Poole et al. (2023) (H1) was confirmed: increasing VAS imposed a greater cost than that found by Poole et al. (2023), where a different set of participants performed the same task on a desktop display without an HMD. This cost difference was observed in the average RT differences at increasing eccentricities; on average around a 3.4 ms/degree difference in RT (11 ms in Poole et al., 2023; 14.4 in the current study); that is, around a 31% increase in RT per degree. It is important to note that the cost was not attributable to more frequent head movements here, as the number of movements/degree did not appear to differ between the two studies within approximately 64° of separation (0.07 vs 0.08 in the current study). Rather we infer that in the current study, a strategically longer time was spent dwelling on each information source to ensure that it was well encoded before a head movement was initiated.

Hypothesis 2 (H2) predicted that with an increasing VAS, head movement frequency would correlate with an increase in RT. This hypothesis was confirmed. However, regarding H2, most intriguing was the effect from 64 to 128°; around 4 head movements per trial were required in either case (Figure 5). The mean RT is longer by around 0.79 s with the larger 128° VAS. We infer that this time increase was likely the result of longer and deeper encoding implemented in order to preserve accuracy, as we did not observe much of a difference in average head movement frequency. This interpretation is supported by the weak, though statistically significant, correlation between head movement frequency and RT ($r \le .4$), indicating that less than 20% of RT variance was shared with head movement frequency. Thus, encoding processes, rather than head movements, likely account for the majority of the RT increase, suggesting strategic effort to stabilize error rates despite greater spatial separation.

As with Poole et al. (2023) we again found a nonlinear trend in head movement frequency at increasing spatial separation distances, such that head movements would increase at separation distances beyond 32° of VAS and stabilize at a constant level (around 4 movements) between 64° and 128°. The drastic increase in head movements from 32° to 64° of separation likely reflects the shift from within to beyond the FOV of the device, and requirements to hold information in memory for a longer span of time where memory decay can take hold, and another head movement may be required to accurately complete the task.

Hypothesis 3 (H3), predicting that an increase in head movements would preserve accuracy, was confirmed. Error rate remained constant at around 8% across all VAS.

Collectively, these findings highlight a more complex relationship between head movements imposed by spatial separation and task type in AR-HMD platforms. We infer that the observed increase in head movements beyond 32° reflects the additional physiological and cognitive effort required when responding to greater spatial separation, leading to more pronounced performance costs. At 64° and 128° of separation, participants on average exhibited longer latencies, characterized by the longer response times, likely indicating repeated viewing of both the coordinate and map locations. This rechecking behavior suggests that information was becoming lost or uncertain due to working memory decay/interference while participants generated and selected their responses.

While these observations provide insight into participants' strategies, another crucial factor that may have influenced their behavior is the physical characteristics of the AR-HMD device. The correlation results likely reflect that the characteristics of the device and task may have made head movements more costly than when presented on a wide-angle desktop display (Poole et al., 2023). Our results may also indicate a difference in stabilization requirements when using an AR-HMD. Specifically, there may be a jitter or streaking effect of the displayed information in an AR-HMD format. Lutwak et al. (2023) found that added jitter with the HL2 becomes significantly more noticeable when virtual objects are rendered closely in front of a flat wall surface compared to when floating in virtual space, and that movements also increased perceptual sensitivity to jitter. Regan and Miller (2017) demonstrated that the streaking effect, where the image appears more blurred due to low refresh rates, occurs when head movements are faster than the device can keep up with, and noted that even refresh rates as high as 60 Hz (similar to the HL2 used in the current experiment) can cause visible smearing. In the current experiment renderings were placed in front of a white wall background and required further lateral head movement requirements than other recent work conducted on direct desktop to HMD comparisons (Warden et al., 2024). Stabilization requirements may have also had a bigger impact here due to the increased encoding requirements and the need to devote greater visual attention to perform spatial estimations. Although the current HMD was relatively light weight, its presence still could have led to slightly slower or more cautious head movements (a 31% difference in ms/degree head movement), consistent with observations made by Yeh et al. (2003). It is important to consider that this cost might be amplified in multi-tasking situations, as multi-tasking requirements tend to amplify the detrimental effects of other variables on RT (Wickens et al., 1983).

The current work builds on our understanding of how spatial separation effects interact with both task complexity and display formats (AR-HMD vs. desktop). While prior work shows that head movements are relatively cost-free (Poole et al., 2023; Warden et al., 2024), the current work shows that increasing task complexity results in a cost associated with head movements with an AR-HMD, suggesting an interaction between IAE and information presentation format for tasks with higher visual attention and working memory requirements. These findings aid in quantifying cost functions for AR-HMD use and identify thresholds at which head movements start to result in meaningful response time penalties. These findings have implications for glanceable AR, information accessible at the periphery or with a head-glance (Lu et al., 2020), suggesting that separating information moderately can be tolerable, but increasing separation requires careful consideration, especially in time-sensitive domains like the military or healthcare.

Limitations and Future Directions

The current work is limited in that it was conducted in a controlled laboratory setting with a uniform background to limit the visual complexity of the task, and isolate costs of spatial separation. Future work should seek to generalize to real-world applications, where movement, multi-task requirements, and overlay clutter may contribute to performance decrements, and where information needed for a decision may not always be at the same optical depth (Warden et al., 2024). Also, our assertion that VAS imposes greater penalties with the HMD than with the flat panel display is based on a between-experiment condition. Although every effort was made to assure equivalence in methods and participants between the current experiment and that of Poole et al. (2023), our assertions of HMD-related differences would have greater validity in a within-subjects experiment.

The relationships between optical depth, head movement frequency, and performance, as well as visual stabilization's role in performance for spatially separated, visually demanding information is an important issue for future research to address. So too is the extent to which different scanning strategies may underlie the tendency to rotate, or not rotate the head when information appears in peripheral vision.

Conclusions

These findings offer practical insights for the design of AR-HMD for safety-critical domains, where quick and accurate decision making is important. The design of these devices should consider the cognitive and physiological costs associated with excessive information separation. While positioning displayed content outside of the immediate field of view reduces the influences of clutter, it must be optimized by limiting excessive eye and head movements, especially for tasks requiring spatial integration. The minimal costs when moderate levels of spatial separation are implemented (i.e., 16° to 32° of spatial separation) suggest that AR-HMDs can tolerate some degree of spatial separation, such as that used with glanceable AR (Lu et al., 2020). This work has design implications for where and how to present information to mitigate effort (and thus performance) costs. Given that AR-HMDs showed larger penalties for separation than flat panel displays with a complex integration task, likely partly attributable to longer encoding times, our work suggests that careful evaluation of information placement is warranted to support tasks with high visual attention and working memory demands. The observed VAS costs found here, an increase of around 1.6°s, are likely to amplify under real-world multi-tasking, consistent with literature showing that multi-tasking exacerbates RT impacts from other task-difficulty drivers (Wickens et al., 1983, 2022).

Key Points

- The current experiment was intended to examine the extent to which performance costs for lateral information separation with a spatial integration task transferred from a wide-angle desktop display to an AR-HMD format.
- While a similar pattern of head movement frequency was observed, the role of head movements in an AR-HMD format became more costly to response time, with no effect on accuracy.
- Performance decrements to response time observed on a wide-angle desktop display appear to have been amplified when transitioning to the AR-HMD, presumably attributable to information presentation format.
- These results have implications for display evaluation guidelines, that spatial integration task costs modeled on desktop displays do transfer to an AR-HMD format, but also that the possibility of a task-device interaction may necessitate more thorough evaluation.

Declaration of Conflicting Interests

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