Proceedings of the Human Factors and Ergonomics Society Annual Meeting
2023, Vol. 67(1) 947–952

DOI: 10.1177/21695067231192646
journals.sagepub.com/home/pro
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Information Access Costs with a Wide-Angle Desktop Display

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Abstract

In choosing where to present information on large displays, multiple monitors, and head-mounted displays, the potential arises to create access costs associated with placing information outside of the immediate field of view. The current experiment examined performance tradeoffs associated with increasing information access effort ranging from 16 to 128 degrees of lateral separation on a wide-angle desktop display. During a spatial integration task, participants indicated whether grid coordinate numbers shown in one location on the screen were within a designated zone on a map displayed in another location. Results showed a significant non-linear trend of head movements, a linear trend of response time, and no effect on error, when the two pieces of information were displayed at greater separation distances. These results have implications for designing visual displays, suggesting where information access effort needs to be considered when scanning for information outside of the immediate field of view.

Keywords

Information Access Effort, Attention, Display Design, Effort, Performance, Working Memory, Information Processing

Introduction

Advances in technology are resulting in changes to the ways people are presented with visual information from displays. The increasingly common use of larger displays, multiple monitors, and head-mounted displays offers the potential to present information to users across wider visual areas. In some scenarios the user may be required to integrate information across distinct locations. In such cases, the degree of separation between sources of information can directly impact the user's decision to either rely on their imperfect memory or to access the information directly (Jang et al., 2012). For example, the user may decide to rely on their memory of what was displayed a few seconds ago rather than take the effort to access the most recent information with a head turn to ensure nothing has changed. Given that people tend to be effort averse (Kahneman, 2011), they often choose the less effortful action.

The concept of Information Access Effort (IAE) refers to the amount of cognitive and physical effort required to shift attention between different locations. The amount of effort required to move attention across space depends on the amount of separation between two sources of information (Wickens, 2014). IAE can be reflected using different types of measures, such as the number of keystrokes required to access database information (Ballard et al, 1995; Yang et al., 2014; Seidler & Wickens, 1996) or in terms of time required to maintain and rehearse a phrase in working memory (Wickens, 2007). In the current work, IAE is operationally defined by the visual angle separation (a.k.a. eccentricity) between two sources of information.

Past literature suggests that information access effort over large separations of visual angle results in an effort-induced cost to performance as information moved from the eye field to the head field (Martin-Emerson & Wickens, 1992; Schons & Wickens, 1993; Houtmans & Sander, 1984; Kim et al, 2010; Murata et al., 2018). As accessing information becomes more effortful when moving from the eye field to the head and body fields, performance declines. More specifically, when two sources of information are within 3-5 degrees of each other, the "no scan region", information can be accessed with peripheral vision. However, as the sources of information become more separated at angles up to around 15 to 25 degrees, entering the eye field, eye scanning becomes necessary to bring information into foveal view. When information is further separated by angles beyond this range (i.e., the

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head field), head or even body movements are often required to access information. Effort increases to a greater extent when accessing information requires head movements, torso rotations, or full-body movements (Yang et al, 2015). However, the boundary between the eye and head field and the extent of the effort-induced cost remains uncertain and past studies show considerable variability (Warden et al., 2022). Much of this variability is related to differences in the visual acuity required to extract information from an eccentric location. When such acuity is high, head movements are less necessary.

A study conducted by Draschkow et al. (2021) used a spatial integration task in a virtual reality (VR) simulation with separation ranging from 0 to 135 degrees and found that when controlling for task accuracy, response time significantly increased at eccentric angles as small as 45 degrees. Gaze tracking data revealed that participants incurred a greater cognitive demand by encoding more features into working memory at greater separation distances in order to reduce physiological costs associated with making multiple head movements to access the same information more than once. While this study showed an IAE performance cost to response time associated with spatial tasks in VR environments, it did not examine the effect of this increased IAE cost directly on task accuracy.

The concept of IAE is directly related to the Proximity Compatibility Principle, which states that when two pieces of information must be integrated, they should be placed in closer perceptual proximity to reduce IAE costs (Wickens & Carwell, 1995). Warden et al. (2022) examined IAE performance costs utilizing a 2D desktop display for a computation integration and focused attention task ranging from 2 to 40 degrees of separation. Results showed that response time increased significantly with greater eccentricities for the focused attention task but not for the integration task, and showed no loss in accuracy for either task. A second experiment used the HoloLens 2 head-mounted display (HMD) to assess IAE performance costs and the role of head movements for a focused attention and an integration task ranging from 2 to 50 degrees of separation (Warden et al., 2022). Greater separation distances showed a significant increase in head movements only beyond 32 degrees for the integration task and between 2 and 16 degrees for the focused attention task, with no significant increase in response time or loss in accuracy for either task. These findings show that out to 50 degrees of separation, head movements are able to compensate for IAE performance costs associated with accessing information into the head field for integration tasks involving numeric material.

The current experiment utilizes a more challenging and realistic spatial integration task typical of that imposed on military personnel, in order to examine IAE performance costs at greater separation distances (16, 32, 64, 128 degrees) on a wide-angle desktop display to determine if the expected trend of performance costs emerge at these greater distances with a more complex task, and the extent to which these costs can be offset by head movements.

Based on the prior findings of Warden et al. (2022), we hypothesized (H_1) that increasing visual angles from 16 to 32 degrees would show no difference between response time or accuracy. We also predict that (H_2) at display separations of 32 and greater the increased IAE will increase head movement frequency and impose a cost to response time and accuracy. This is because effort conservation would lead participants some of the time to be reluctant to engage in sufficient head movements to accurately foveate the eccentric stimulus (an accuracy cost), or, if doing so, the head movement being more time consuming than the simple eye movement, would produce a time cost. Lastly, (H_3) IAE costs reflected by head movements would be greatest at 128 degrees of visual separation and, across the full range of visual angles, a non-linear accelerating trend of performance costs would emerge with the largest visual angle imposing the greatest performance costs to accuracy and response time.

Method

Participants

Thirty-three participants enrolled in an undergraduate psychology course at Colorado State University received course credit after completing the experiment. Participants had self-reported normal or corrected-to-normal vision and were screened for colorblindness.

Task

An example of the spatial integration task is illustrated in Figure 1. Participants had to first focus on a fixation cross at either the left or right edge of the display (in the figure, on the right), and immediately clicked the spacebar on a keyboard when their center FOV was fixated at the cross. Once the space bar was pressed a map with an 8 x 8 grid layout, a red (danger) zone, and numbered gridlines immediately replaced the fixation cross and a grid coordinate number simultaneously appeared at one of four degrees of separation (16, 32, 64, and 128 degrees) from either the left or right side of the map. When the map appeared on the left edge of the display the coordinates appeared to the right of the map. When the map appeared on the right edge of the display the coordinates appeared to the left of the map, as shown in the figure. Participants responded with a “Y” key press if the coordinate’s location was in the red zone and with a “N” key press if it was not. Prior to the start of the experiment, participants were instructed to respond as accurately and rapidly as possible. Figure 1 represents the 16-degree separation condition. With the wider separations (not shown here) the space between the map and the coordinates was blank.

Participants completed two counterbalanced blocks that presented the map at either the left or right edge of the

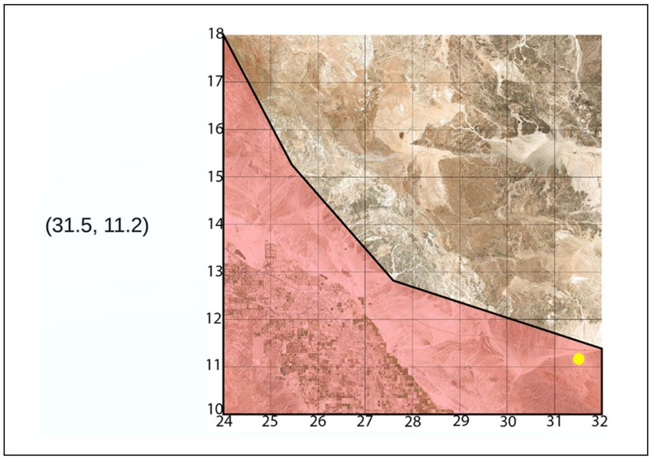

Figure 1. An illustration of a single trial for the spatial integration task consisting of a map (right) and the grid coordinate (left) separated by 16 degrees. The yellow dot represents where the grid coordinate **would be located** on the map but was not present in the experiment. Participants estimated the approximate location from the given coordinates.

display. Each block began with 8 practice trials with auditory feedback on correct or incorrect responses. Each block consisted of four subblocks, one for each level of separation. For each display separation subblock, participants viewed 24 trials and one attention check trial, different (randomized) red zone contours and grid reference numbers, and a different 6-digit grid coordinate location for each trial. Display separation subblocks were counterbalanced, and the trials within each subblock were randomized. Participants completed a total of 216 trials. Participants were given the option to take a 60-second break between each map separation subblock. The entire experiment lasted approximately 60 minutes.

Stimuli and Apparatus

Participants completed the experiment using a Samsung 49” Odyssey Neo G9 Gaming DQHD Quantum Mini-LED Monitor, a wide-angle 2D desktop display. The experiment was programmed using Unity (2022.1.10f1). We generated 8 unique map images using the website caltopo.com, an online application used to create topographic maps based on geospatial databases. As shown in Figure 1, each map consisted of a desert terrain background and had 8 grid lines evenly separated in vertical and horizontal directions. Grid lines corresponded to grid coordinates that ranged from 10-49. To accommodate non-military participants, each 6-digit grid coordinate was modified from the standard Military Grid Reference System (MGRS, e.g., 478221) to include a comma separation between horizontal and vertical grid axes values and a decimal point between the second and third horizontal or vertical coordinate value (e.g., 47.8, 22.1).

Maps were 1149 x 1149 pixels and varied in complexity based on the number of lines which created the border for the red zone, and the location of the red zone. Coordinates located inside of the red zone indicated a threat. Red zone lines ranged from low to high complexity, consisting of either 3, 7, or 10 lines that consisted of vertices that were 90 degrees or larger or that were curved. Each coordinate location was uniformly distributed with varying distances from the red zone line, ranging from low to high uncertainty to create discrimination problems of varying levels of difficulty. Maps were presented at either the far left or far right edge of the display. The center of the coordinate numbers was positioned at either 16, 32, 64, or 128 degrees to the right or left of the map, respectively, from the center of the map image. All stimuli were presented on a white background.

Procedure

All participants gave informed consent to participate before the experiment and completed an electronic version of the Ishihara colorblindness test. Participants were trained on how to determine locations using a map with 6-digit grid coordinates. Participants were seated 15.5 inches from the center of the display to ensure a maximum visual angle of 128 degrees. They were instructed to maintain the same posture and distance from the display throughout the experiment.

Results

Data for the spatial integration task and head movements were analyzed in R using separate one-way repeated measures ANOVAs. Participant responses for information displayed from both sides of the display (i.e., rightward and leftward head movements) were combined prior to analysis. Outlier criteria for participant response time was determined by responses below 300 ms or higher than 1.5 times the upper bound of the interquartile range. The lower bound response time criteria is based on response times being physiologically limited due to time necessary for encoding and response execution (Berger & Kiefer, 2021; Ashby & Townsend, 1980). Prior to analysis 260 trials were determined to be outliers and removed from the data. Response time was recorded from when participants pressed the space bar to start the trial until they responded. Response time data were log-transformed to correct for the positive skew.

Effect of Display Separation on Performance

Response Time. Mean response time is plotted as a function of lateral display separation in Figure 2. A one-way repeated measures ANOVA showed a large and significant main effect of display separation on log-transformed response time, $F\,(1.88, 60.21) = 16.05, p < .01, \eta 2 = .09$. Consistent with an information access effort cost, response time increased as display separation increased.

A series of one-tailed pairwise t-tests showed no significant difference in response time between 16 and 32 degrees

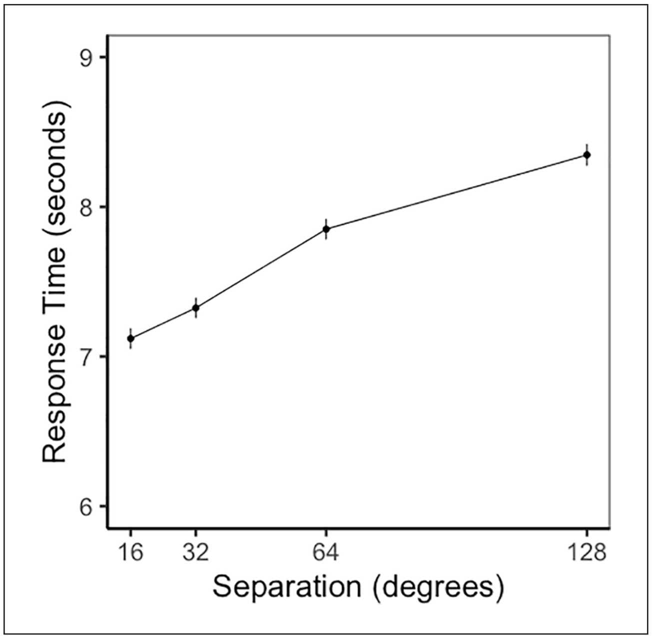

Figure 2. Mean response time (measured in seconds) plotted as a function of lateral visual separation. Error bars represent one standard error of the mean.

of separation ($t(32) = -1.90$, $p = .07$, $d = -0.18$). However, there was a significant increase across the larger angle from 32 to 64 ($t(32) = -3.53$, $p < 0.01$, $d = -0.33$), and from 64 to 128 degrees of separation ($t(32) = -2.28$, $p = .03$, $d = -0.31$). Thus, the graph indicates that RT as a function of visual angle is essentially linear.

Percent Error. The mean error rate across all conditions was 91%. A one-way repeated measures ANOVA showed no significant effect of display separation on percent error, $F(1.8, 57.75) = 1.34$, $p = .27$, $\eta 2 < .01$. There was no cost to percent error as display separation increased. Furthermore, the increase in response time at the largest visual angle did not significantly reduce the error rate.

Effect of Display Separation on Head Movements

Partially aligning with our predictions, increased separation between two sources of information imposed a cost to response time. However, there was no cost to accuracy as display separation increased. To help explain why there was no cost to accuracy, we examined the role of head movements. The experimenter recorded head movements by monitoring participants during the experimental trials. A single head movement was recorded when participants moved their head from the map at the start of the trial to the coordinate grid presented to the left/right of the map. Mean number of head movements per trial are plotted as a function of lateral display separation in Figure 3. A head movement was defined as a single movement in either direction. A one-way repeated measures ANOVA showed a large and significant main effect of display separation on the average number of head movements, $F(2.11, 67.46) = 83.69$, $p < .01$, $\eta 2 = .56$. As the figure reveals, the number of head movements per trial linearly increased as visual angle increased from 16 to 32 degrees ($t(32) = -6.17$, $p < .01$, $d = -0.74$), and from 32 to 64 degrees ($t(32) = -9.29$, $p < .01$, $d = -1.57$) but then abruptly levels off between 64 and 128 ($p = .93$).

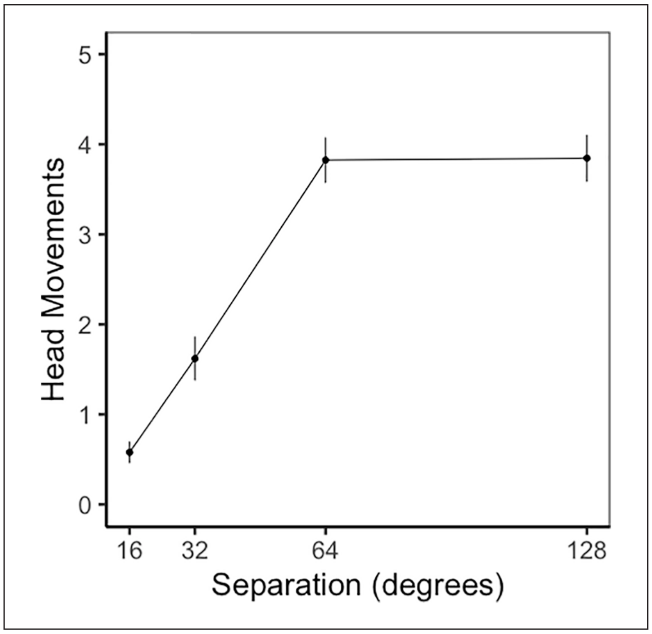

Figure 3. Mean head movements per trial plotted as a function of display separation. Error bars represent one standard error of the mean.

Correlational Analyses. There was considerable variation between individuals in the frequency of head movements, as shown by the large standard error bars in Figure 3, particularly at 32 degrees. We were interested in the extent to which those who made more head movements (a) took longer because of the time cost of head movements and (b) were more accurate because head movements might compensate for any failures of working memory. The data revealed that the correlation between head movements and response time was not significant ($p = .52$) nor was the correlation between head movements and accuracy ($p = .41$). Finally, the correlation between response time and error rate was significant ($t(31) = 2.31$, $p = .03$, $r = .38$) suggesting a speed-accuracy tradeoff between participants: those who took longer were more accurate. A similar pattern of findings was observed at other visual angles.

Discussion

The current experiment examined the performance costs associated with increased IAE for a spatial integration task presented on a wide-angle desktop display. A small number of studies suggest a performance cost associated with increased display separation (Wickens et al., 2002; Draschkow et al., 2021; Schons & Wickens, 1993; Martin-Emerson & Wickens, 1992; Houtmans & Sander, 1984; Murata et al., 2018; Murata & Kohno, 2018; Large at al., 2016). However, some recent work has demonstrated that head movements play a critical role in preventing or minimizing the predicted performance decrements in either speed or accuracy, as display separation increases (Warden et al., 2022).

In the current experiment, we examined three hypotheses related to the three different regions of the information access function defined by the visual angle of separation (VAS). H_1 postulated little loss in performance within the approximate VAS range examined by Warden et al. (2022), because of the compensating role of head movements, and this was generally confirmed. There was no loss of accuracy between 16 and 32 degrees of separation, while there was only a trending, but not significant ($p = .07$) increase in response time. Head movements in contrast more than doubled in frequency from 16 to 32 degrees of separation, such that the modal response at 32 appeared to be slightly less than 2, as if the participant typically looked at the map, then at the coordinates and then back to the map to determine the coordinates location before responding.

H_2 predicted greater head movements and costs to performance would occur at 32 degrees of separation and beyond. Results show that head movements are always evoked in this range and again, the increase in head movements approximately doubled. The hypothesis regarding performance was partially confirmed because this increase did create a significant increase in response time, but again, accuracy was preserved at a constant level of 91%.

H_3, predicting the larger increase in head movements from 64 to 128 and a larger cost to performance accuracy was generally disconfirmed. Accuracy remained constant, but this preservation of accuracy at the widest separation was accomplished without making more head movements. However, there was a cost of time. In our interpretation, this cost **did** reflect the cost of head movements in an indirect way. We infer that, in order to prevent having to make more (costly) long head movements across the full 128 degrees of the large screen, which imposed some resistance by the neck, participants preferred to focus their visual attention for a longer time on each of the two stimuli, to assure better encoding, and hence better buffer the quality of the image from the degrading memory effects of the passage of time. This is a short "micro-strategy" so to speak, to cope with the need for more head movements, and one that was nevertheless successful. This micro-strategy may also explain why head movements peaked at four: viewing the coordinates for a longer amount of time allowed for better encoding of the numbers and, therefore, reducing the need for more head movements.

Beyond the three hypotheses, another way to look at the collective data across all four separations is to consider what is clearly a linearly increasing function of response time (Figure 2), with no evidence for an accelerating trend in either that function or in the flat error function (constant at 9%). Such linearity was not predicted by the original eye-head field dichotomy but was in fact obtained in a different context by Kim et al (2010), who observed that the proportion of scans-with head movements increased linearly, with no discontinuity or acceleration across the entire range of lateral visual angles from 0 to 80 degrees. Thus, out to 64 degrees, the costs of head movements are indeed quite low (but not zero, as the interpretation above explains).

A second comparison of the global data from the current experiment is to contrast the relatively large increase in head movements/second (the slope of the function in Figure 3), with a much smaller value observed across an equivalent range by Warden et al. (2022). We attribute this difference to the difference in task difficulty. In the current experiment, participants were required to retain 6 digits in working memory during the scan for comparison with the spatial coordinates on the map. In Warden et al. (2022), it was only a single 2-digit number. Such a difference in task difficulty is confirmed by the greater error rate observed here (9%) than in the prior study (around 5%). And the greater memory load imposed here, presents a greater requirement for head movements.

Conclusions & Limitations

The current results speak to both the benefits and constraints to wide screen displays or multi-monitor workstations. Costs from the separation of information are relatively low when subtending visual angles out to around 60 degrees. But beyond that, they may be constrained by excessive head movements which users are reluctant to undertake. Such a conclusion, favorable to angles as large as 60 degrees can extend to a large virtual space commanded by an AR-HMD as reflected in "glanceable AR" (Lu et al., 2020); with the caveat that here, large head movements, beyond the 40-degree angle examined by Warden et al. (2022), may be encumbered by the weight of the device (Yeh et al., 2003). This extension in visual angle of virtual space with the HMD is currently being examined. Greater sensitivity in future research could be obtained through the inclusion of more sophisticated measures of head movements via accelerometers or post-experiment video analysis.

Acknowledgments

This research was supported by the Office of Naval Research under grant numbers N00014-21-1-2949 and N00014-21-1-2580. Dr. Peter Squire was the scientific/technical monitor.

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