Information Access Effort: Are Head Movements “Cheap” or Even “Free”?

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Augmented reality head-mounted displays (AR-HMDs) can present information at the center field of view (FOV) to 360° around the user. Deciding where to place virtual content when using an AR-HMD could directly impact the effort required to access information for different tasks. The current paradigm investigated the cost of information access effort for two different tasks presented on a virtual display using an AR-HMD. Participants made comparison judgments for two types of tasks (focused attention and computation integration) based on information presented at increasing lateral distances from the left side of the virtual display. Results showed no loss in performance as predicted by the Information Access Effort function. However, results show that evoking head movements played a significant role in restoring and preserving accuracy at greater visual eccentricities without hindering response time.

INTRODUCTION

While driving in heavy traffic, you realize you need to change lanes. After a glance at your rearview mirror, you see an empty lane and proceed to change lanes until you hear a loud horn from the driver behind you. You failed to check your blindspot, an action requiring head and torso rotation to access the necessary information. Instead, you relied on the less effortful action of quickly glancing in the rearview mirror. Choosing the less effortful action occurs because people tend to be effort averse (Kahneman, 2011), such as relying on an imperfect memory instead of searching for a book to find a precise reference when writing a manuscript.

The concept of **Information Access Effort** (IAE) describes the mental or physical effort required to move attention from information in one location (the heading of a vehicle) to information in another location (the rearview mirror or blindspot). IAE varies as a function of the distance, defined by visual angle, between two sources of information. The present research focuses on the concept of IAE in the specific context of an augmented reality head-mounted display (AR-HMD). This concept of IAE is relevant to HMDs in two key ways: (1) Where information is placed on the viewing space depicted by the HMD relative to the central field of view (FOV). For example, glanceable AR may be positioned at a visual angle beyond the momentary HMD FOV (Lu et al., 2020); (2) How much of a performance benefit occurs when overlaying imagery of the HMD onto the real world relative to presenting information on a head-down display (e.g., tablet or smartphone), with substantial head movement required to access it. Both factors quantitatively impact the IAE and thus require establishing an IAE function in the context of HMDs.

Past literature indicates that information access over large separations of visual angle imposes a nonlinear trend conveying an effort-induced cost, as depicted in Figure 1 (Martin-Emerson & Wickens, 1997; Schons & Wickens, 1993; Houtmans & Sander, 1984; Kim et al., 2010; Murata et al., 2018; Murata & Kohno, 2018; Large et al., 2016; Wickens, 1993; Wickens et al., 2003). If two spatially separate sources of information are within approximately 3° of each other, peripheral vision with no eye movement (“no scan region”) is sufficient to access information. When information is separated by up to 20-25° (within the “eye field”), eye scanning will be required; beyond this approximate boundary, head and body movement will be required. Engaging eye scanning is often described as “cheap” given its low effort, but if a lot of eye scanning is required to access information due to increased separation, eye scanning becomes more effortful, and the likelihood that people will invoke an eye scan decreases. That is, eye scans may be “cheap,” but they are not “free.” Effort increases to a greater extent when accessing information that requires head movements, torso rotation, and full-body movements (Yang et al., 2015). The effort-induced cost of greater IAE is well established in the literature. For instance, during a simulated programming task, people preferred to rely on their imperfect memory rather than perceptually accessing information through minor actions such as a mouse click or an eye scan (Gray & Fu, 2004, also see Ballard et al., 1995 and Draschgow et al., 2021). Kim et al. (2010) have carefully examined the differential contributions of eye and head movements at increasing visual angles, but they examined physiological measures of effort rather than performance.

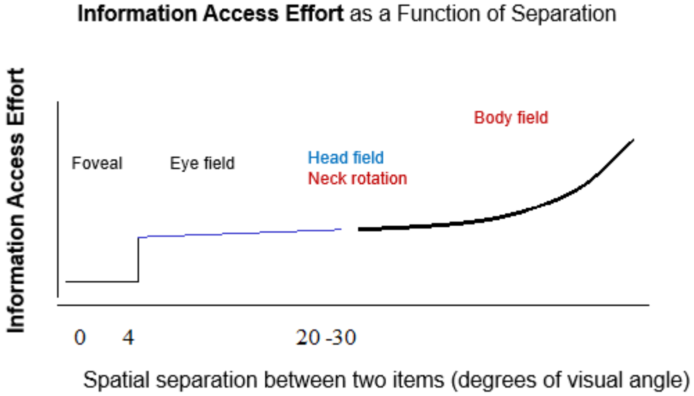

Figure 1. Illustration of the IAE function. Long, effortful scans inhibit scanning and initiation of the head field.

One fundamental design goal for both the head-mounted display (HMD) and head-up display (HUD) is to reduce the amount of scanning (and hence IAE) required between the near domain (the display) and the far domain (the external world) when compared to a head-down display which presents information away from the forward field of view (e.g., on a tablet or smartphone). Reduced IAE of superimposed imagery of the HMD (or HUD) is not the only effect of superimposition (i.e., overlay) relative to a head-down display: overlaying information imposes a cost of clutter. While clutter costs are not directly examined in the present experiment, overlaying information in the forward FOV of the near domain can hinder resolution of information in the far domain, ultimately decreasing performance. The tradeoff between IAE and clutter, known as the scan-clutter tradeoff, has been examined in the context of HUDs but not examined for HMDs specifically.

One meta-analysis examining the effects of HUDs versus head-down displays in the context of cars and airplanes found a benefit for the HUD compared to the head-down display, despite the costs of clutter due to information overlay (Fadden et al., 2000). In addition, another important variable moderating the extent of the HUD benefit included the type of attention required for the task: focused or integration (Fadden et al., 2000). The HUD benefit was more advantageous when the two sources of information had to be **integrated**, such as a HUD cue pointing to an object on the runway, compared to when the two sources of information required independent processing, such as when **dual-tasking** or **focusing attention** on one domain, like monitoring the altitude of an aircraft. These findings suggest an interaction between display separation (measured in visual angle) and task type (integration versus focused attention) as defined by the **proximity compatibility principle** (Wickens & Carswell, 1995; Wickens, 2021; Kroft & Wickens, 2003). This principle proposes that when information from two sources requires integration, information should be placed closer in proximity (e.g., overlaid). In contrast, when the task requires focusing on one source of information, that information should be more separated (e.g., head-down display) to reduce the clutter imposed by overlaying information.

The effect of display separation on IAE when using AR-HMDs remains unclear. AR-HMDs possess the capability of overlaying information in the near and far domain or positioning virtual content out of the forward FOV, as with the concept of "Glanceable AR" (Lu et al., 2020). Positioning the virtual content of an AR-HMD is an important decision. While overlaying information minimizes the cost of scanning, overlaid information can obscure information in another domain, thereby reducing legibility and ultimately imposing a cost of clutter. Designers have opted to place some virtual content near the periphery or beyond the display (Lu et al., 2020) to avoid clutter costs. However, locating information in other areas could increase scan time and cause fatigue when accessing information over time. Quantifying this scan-clutter tradeoff is necessary when designing and using AR-HMDs for different tasks.

The scan-clutter tradeoff exhibited for integrated and focused attention tasks makes specific predictions about performance measures (i.e., response time and accuracy). First, an increase in IAE predicts a nonlinear increase in response time at further distances due to the increased effort required to access information via eye scan, head, or body rotation. Second, an increase in IAE predicts a decrease in accuracy due to: (1) the potential for people to rely on the low resolution of peripheral vision if they choose not to invoke an eye scan or head movement to bring information into foveal vision to ensure higher acuity; and (2) an increased load on working memory (WM) when scanning or moving back-and-forth to obtain information from both sources during an information integration task. Draschgow et al. (2021) examined the impact of IAE on WM during a task that required locating objects at various ranges of visual angles (i.e., display separations) from 45° to 135° to use in their workspace. They found that when visual angles were large, requiring more effort and time, people relied on WM more than when visual angles were small. This finding suggests that greater visual angles cause people to rely more on WM at the cost of accuracy, particularly for an integration task. Thus, a third prediction is that the cost of scanning is greater for integration tasks than one requiring focused attention.

In the current experiment, we evaluated the cost of IAE when using an AR-HMD with the information presented at different visual angles during two types of tasks: a focused attention task and a computation integration task. We hypothesized (H_1) a nonlinear relationship between smaller visual angles within the eye-field (2° to 16°) and larger visual angles within the head-field (beyond 16°) for response time and accuracy or error rate (Figure 1), (H_2) the cost of greater IAE on response time and accuracy will be larger for the integration task compared to the focused attention task, and (H_3) head movements will be evoked at separations between 16° and 32° and amplified beyond this range.

METHOD

Participants

Twenty-six students enrolled in an introductory psychology course at Colorado State University received course credit after completing the experiment. All participants had self-reported normal or corrected-to-normal vision.

Task

Participants completed the experiment using the HoloLens 2 (AR-HMD), a mixed-reality headset developed by Microsoft Corporation that overlays virtual content onto the far domain. The HoloLens 2 has a lateral FOV of 43° and a vertical FOV of 29°. The virtual display was 29.5 inches by 15.5 inches and positioned on a wall 31.6 inches away from the participant's line of sight to ensure a maximum lateral visual angle of 50°.

The **focused attention** task consisted of a main task and a secondary task. During each trial, a red fixation cross was presented at the left edge of the virtual HMD display for 3 seconds, and a single 2-digit number was presented randomly in the rightward lateral direction at one of four degrees of separation (2°, 16°, 32°, 50°) from the fixation cross. There were 3 seconds between each trial. The 50° separation was qualitatively different from the other lower values because here, the stimulus was out of the initial FOV of the HMD at the start of the trial, and hence, head movement was mandatory rather than optional to perform the task. As a secondary task, the red fixation cross jittered back and forth zero, one, or two times. For the main task, participants had to indicate whether the single 2-digit number was "less than" or "greater than" 45 by pressing the 'Q' and 'P' keys, respectively, on a wireless keyboard. The secondary task was to ensure that participants fixated on the left edge of the virtual display at the start of each trial by requiring them to monitor the fixation cross and press the 'spacebar' key whenever the cross jittered.

For the **computation integration** task, participants were asked to mentally compute the absolute value of the difference between two numbers. To ensure participants fixated at the left edge of the virtual display, a XX appeared at that location and was rapidly replaced by the first 2-digit number. After 3 seconds a second 2-digit number also appeared randomly at one of the four degrees of separation (2°, 16°, 32°, 50°) displaced to the right from the first number. There were 3 seconds between each trial. Using the same keypresses as above, participants indicated whether the difference between the two numbers was "less than" or "greater than" 37.

Participants completed two cycles. Each task consisted of 16 practice trials and 56 test trials for the first cycle. The practice trials provided auditory feedback on correct and incorrect responses. For the second cycle, each task consisted of 56 test trials. The entire experiment consisted of 256 trials and lasted approximately 30 minutes. The two tasks were counterbalanced, and the presentation order of the display separation was blocked within each task. Display separation blocks were randomized, and trials within each display separation block were randomized. Participants could take an optional 60-second break between the two cycles.

Procedure

All participants gave informed consent before starting the experiment. After putting on the AR-HMD, they were seated 31.6 inches in front of a wall. The instructions for both tasks were presented on the AR-HMD virtual display and stressed the importance of the secondary (jitter detection) task, and the requirements for both the focused attention and integration task, as described above.

RESULTS

Data from both tasks were analyzed in R using separate one-way repeated measures ANOVAs. Data from one participant were removed because that participant had chance accuracy for all levels of display separation. Additional outlier criteria were based on whether a response time was 1.5 times beyond the upper bound of the interquartile range (IQR) or below 300 milliseconds for each task. A total of 337 trials (approximately 5%) were removed. Before analyzing response time, we log-transformed the response time data given that the data were positively skewed. Response time was measured from the onset of the target stimuli until participants made a keypress response.

Focused Attention Task

Response Time. The effect of display separation on response time and percent error for the focused attention task are presented in Table 1 (top rows). An ANOVA showed no significant effect of display separation on the log of response time, F(3, 72) = 2.10, $p = .10$, $\eta_p^2 = 0.08$

Percent Error. The ANOVA showed no significant effect of display separation on percent error, F(3, 73) = 0.96, $p = .42$, $\eta_p^2 = 0.04$, as shown in Table 1.

Table 1.
Descriptive statistics for performance measures (response time measured in seconds and percent error) as a function of task type and display separation.

	Display Separation (degrees)			
	2°	16°	32°	50°
Focused Attention Task				
Response Time (s)	1.15 (0.02)	1.15 (0.03)	1.22 (0.04)	1.10 (0.02)
Percent Error (%)	2.89 (0.58)	4.68 (0.45)	3.57 (0.65)	3.56 (0.88)
Integration Task				
Response Time (s)	4.24 (0.11)	4.21 (0.11)	4.16 (0.08)	4.18 (0.09)
Percent Error (%)	15.8 (1.32)	19.0 (1.32)	17.5 (0.81)	14.6 (1.32)

Secondary Task. The secondary task was designed to ensure that participants fixated on the left side of the display at the beginning of each trial. Neither response time (M = 0.67 s) nor accuracy (M = 76%) of the secondary task was significantly affected by visual separation of the primary task (both *ps* > .50).

Computation Integration Task

Response Time. The effect of display separation on response time for the computation integration task is presented in Table 1 (bottom rows). There was no significant effect of display separation on the log-transformed response time, F(3, 72) = 0.07, $p = .98$, $\eta_p^2 < 1.0$.

Percent Error. The effect of display separation on percent error was also not significant, F(3, 72) = 1.90, $p = .14$, $\eta_p^2 = 0.07$ (Table 1). There was no cost in performance for percent error as display separation increased. In fact, the data (Table 1 bottom rows) revealed a non-significant trend in which people became more, rather than less, accurate at greater degrees of eccentricity beyond 16°.

Next, we conducted a 2 (task type) x 4 (display separation) repeated measures ANOVA to assess whether performance differed between tasks. The ANOVA showed a large effect of task type on the log-transformed response time, F(1, 24) = 180.60, $p < .001$, $\eta_p^2 = 0.88$, with 2.91 seconds slower performance for the more difficult integration task. Neither the effects of display separation nor the interaction between display separation and task type was significant (*ps* > .20). An ANOVA also showed a large effect of task type on percent error, F(1, 24) = 29.1, $p < .001$, $\eta_p^2 = 0.55$, with 13% more errors for the integration attention task.

To look at the consistent trend of increasing error rate from 2° to 16° for both tasks (Table 1) (i.e., within the eye field), we conducted a 2 (task type) x 2 (display separation) repeated measures ANOVA which showed a significant increase in error as display separation increased, exclusively within the eye field, F(1, 23) = 4.35, $p = .048$, $\eta_p^2 = 0.16$.

Combined Analysis: Head Movements

Contrary to our predictions, performance on both tasks showed a non-significant trend to become more accurate as display separation increased beyond the eye field, without negatively impacting response time. To help explain why there was no cost in performance, we examined the role that compensatory head movements played during each task by conducting a 2 (task type) x 4 (display separation) repeated measures ANOVA. Figure 2 presents the mean number of head movements for both tasks, superimposed to indicate the commonality of the trends between the two tasks.

There was a large effect of display separation on head movements, F(3, 69) = 93.04, $p < .001$, $\eta_p^2 = 0.80$. The number of head movements increased monotonically as visual angle increased, particularly from 32° to 50° (*ps* < .001), this latter effect to be expected given that the 50° condition was out of the initial FOV (i.e., initially invisible). There was no significant effect of task type on the number of head movements. However, there was a significant interaction between display separation and task type, F(3, 69) = 6.37, $p < .001$, $\eta_p^2 = 0.22$. When the visual angle increased from 2° to 16°, participants only significantly increased head movements during the focused attention task, *t*(23) = 2.84, $p = .01$, 95% CIs [0.56, 3.58], $d = 0.81$. Conversely, when the visual angle increased from 32° to 50°, more head movements were made with the integration task than with the focused attention task, *t*(23) = -3.07, $p = .005$, 95% CIs [-12.45, -2.42], $d = 0.59$.

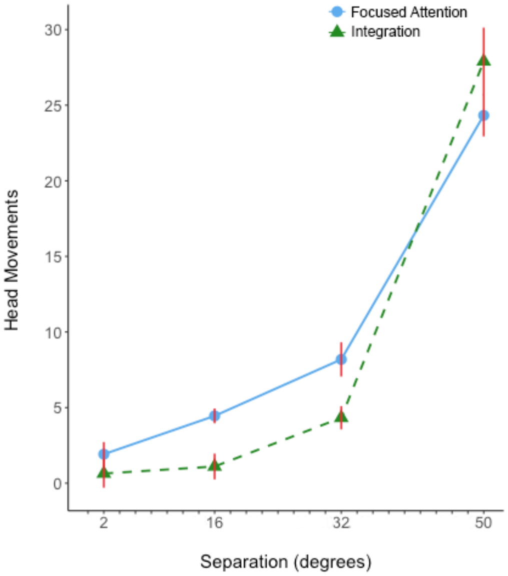

Figure 2. Mean number of head movements plotted as a function of display separation for the computation integration task (green triangles, dashed line) and the focused attention task (light blue circles, solid line). Error bars represent one standard error of the mean.

DISCUSSION

The current experiment examined the IAE function defined by the visual angle (Figure 1) with its amplified growth from the eye field to the head field. Specifically, would the function revealed in flat panel displays be expressed in viewing virtual displays presented with an AR-HMD? Expectations for the same trend have been revealed in a small number of studies (Wickens et al., 2002; Draschgow et al., 2021; Schons & Wickens, 1993; Martin-Emerson & Wickens, 1992; Houtmans & Sander 1984; Murata et al., 2018; Murata & Kohno, 2018; Large et al., 2016), although the trends across these have been inconsistent. Unexpectedly, across the entire range of visual angle separations from 2° to 50°, we found that the function was not replicated in either response time or accuracy hence disconfirming H1. Instead, these data show a trend that participants either restored or preserved accuracy at visual angles within the head field (32° to 50°). However, the error function did show a significant increase in both tasks with increasing visual angle within the eye field but not within the head field. Longer eye movements appear to exert a cost in accuracy.

We interpret the absence of general performance loss with increasing IAE in the head field and the difference in accuracy effects between the eye field and head field in terms of the compensatory role of head movements (Kim et al., 2010). Figure 2 showed that head movements were rarely employed at eccentricities of 16°, particularly for the integration task. Thus, participants presumably employed only visual scanning to bring the second stimulus into foveal vision. However, such scanning was presumably often inadequate, yielding the observed loss in accuracy for the focused attention task. Once the head field was entered, at 32°, neck rotation achieved an entirely successful compensation to bring the second stimulus into complete (and hence accurate) foveal vision confirming Hypothesis 3. The only surprise here was why there was no cost to response time. It may be that making a head movement effectively brought the second stimulus into foveal vision and thereby increased the resolution of the information quickly enough to allow them to respond without hindering response time. These findings are consistent with the idea that people may avoid head movements not because of the time costs associated with them, but rather because of physiological costs. That is, people do not fail to look in the blindspot of their car because of the cognitive effort associated with doing so (e.g., time), but rather the physiological costs of making a head movement or torso rotation. Also, this null effect speaks favorably to both the lightweight and low inertia of the Hololens 2 AR-HMD and to the concept of Glanceable AR (Lu et al., 2020) and presenting information via an AR-HMD, in general.

Although the integration task, as hypothesized (H2), was more mentally challenging (conveyed by its lower accuracy) than the focused attention task, this greater difficulty did not appear to influence the IAE cost function in a way predicted by the proximity compatibility principle (i.e., greater IAE slope for the integration task); although there was no slope in the first place to increase. We might argue then, assuming that the effort demands of IAE were indeed low, there would be little resource competition between the working memory demands of the integration task and the effort of information access to the more peripheral locations. Hence no increase in the slope of the function for the integration task.

One final important difference between the absence of IAE cost here, and its presence found in prior research, is that most of those studies cited above employed vertical displacement, whereas the current study examined lateral displacement. Studies that have compared lateral with vertical displacements have found a greater cost with vertical displacement (Wickens et al., 2002) and observed greater muscular activity (measure via EMG) with vertical displacement (Kim et al., 2010). We intend to replicate the current study with vertical displacement.

CONCLUSIONS

While we did not find the expected loss in performance as predicted by the IAE function (Figure 1), we did find that head movements played an important role in restoring and preserving accuracy without hindering response time. These findings suggest a smaller than expected IAE cost when using an AR-HMD for tasks requiring integrating information between two sources or focusing attention on a single source of information. It may be the case that eye scanning and, particularly, head movements are “cheaper” than previously expected, if not entirely free. It may also be the case that the costs of clutter, which are inherent with AR-HMDs, will play a bigger role concerning the scan-clutter tradeoff. These findings have implications for design guidelines for AR-HMD for tasks that require either focusing attention or integrating information. Future work should seek to directly test the role of clutter in the scan-clutter tradeoff when using an AR-HMD. In addition, future work should also test whether these results would generalize to other scenarios (e.g., tasks conducted in the real world).

LIMITATIONS

There were limitations to the current experiment. We chose to use a blocked design when presenting the different display separations because this design appeared ecologically valid (e.g., consider working with multiple virtual displays that are fixed in space, as is the case with glanceable AR). However, future work should also assess the impact of increasing display separation when the presentation is randomized. Another limitation is that our indirect measure of head movement was recorded across each display separation but not for each trial. Future work should employ head tracking to examine the rate of change in head movements across trials. Lastly, future work should span a greater extent of head movement.

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REFERENCES

Ballard, D. H., Hayhoe, M. M., & Pelz, J. B. (1995). Memory Representations in Natural Tasks. *Journal of Cognitive Neuroscience*, *7*(1), 66–80. https://doi.org/10.1162/jocn.1995.7.1.66

Draschkow, D., Kallmayer, M., & Nobre, A. C. (2021). When Natural Behavior Engages Working Memory. *Current Biology*, *31*(4), 869-874.e5. https://doi.org/10.1016/j.cub.2020.11.013

Fadden, S., Wickens, C. D., & Ververs, P. (2000). Costs and Benefits of Head up Displays: An Attentional Perspective and a Meta Analysis. SAE Technical Paper 2000-01-5542. https://doi.org/10.4271/2000-01-5542

Gray, W. & Fu, W. T. (2004). Soft constraints in interactive behavior: The case of ignoring perfect knowledge in-the-world for imperfect knowledge in-the-head. *Cognitive Science*, *28*(3), 359–382. https://doi.org/10.1016/j.cogsci.2003.12.001

Houtmans, M. J. M., & Sanders, A. F. (1984). Perception of signals presented in the periphery of the visual field. *Acta Psychologica*, *55*(2), 143–155. https://doi.org/10.1016/0001-6918(84)90064-7

Kahneman, D. (2011). Thinking, fast and slow. Farrar, Straus and Giroux.

Kim, K. H., Reed, M. P., & Martin, B. J. (2010). A model of head movement contribution for gaze transitions. *Ergonomics*, *53*(4), 447–457. https://doi.org/10.1080/00140130903483713

Kroft, P., & Wickens, C. D. (2003). Displaying multi-domain graphical database information: An evaluation of scanning, clutter, display size, and user interactivity. Information Design Journal, 11(1), 44–52. https://doi.org/10.1075/idj.11.1.06kro

Large, D. R., Crundall, E., Burnett, G., Harvey, C., & Konstantopoulos, P. (2016). Driving without wings: The effect of different digital mirror locations on the visual behaviour, performance and opinions of drivers. *Applied Ergonomics*, *55*, 138–148. https://doi.org/10.1016/j.apergo.2016.02.003

Lu, F., Davari, S., Lisle, L., Li, Y., & Bowman, D. A. (2020). Glanceable AR: Evaluating Information Access Methods for Head-Worn Augmented Reality. *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 930–939. https://doi.org/10.1109/VR46266.2020.00113

Martin-Emerson, R., & Wickens, C. D. (1992). The Vertical Visual Field and Implications for the Head-Up Display. *Proceedings of the Human Factors Society Annual Meeting*, *36*(18), 1408–1412. https://doi.org/10.1177/154193129203601810

Murata, A., Doi, T., & Karwowski, W. (2018). Enhanced performance for in-vehicle display placed around back mirror by means of tactile warning. *Transportation Research Part F: Traffic Psychology and Behaviour*, *58*, 605–618. https://doi.org/10.1016/j.trf.2018.07.003

Murata, A., & Kohno, Y. (2018). Effectiveness of replacement of automotive side mirrors by in-vehicle LCD–Effect of location and size of LCD on safety and efficiency–. *International Journal of Industrial Ergonomics*, *66*, 177–186. https://doi.org/10.1016/j.ergon.2018.03.010

Schons, V. & Wickens, C.D. (1993). Visual separation and information access in aircraft display layout (Technical Report ARL-93-7/NASA-A3I-93-1). Savoy, IL: University of Illinois, Aviation Research Laboratory.

Wickens, C.D. (1993). Cognitive factors in display design. *Journal of the Washington Academy of Sciences, 83*(4), 179-201.

Wickens, C. (2021). Attention: Theory, Principles, Models and Applications. *International Journal of Human–Computer Interaction*, *37*(5), 403–417. https://doi.org/10.1080/10447318.2021.1874741

Wickens, C. D., Dixon, S. R., & Seppelt, B. (2005). Auditory Preemption versus Multiple Resources: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *49*(3), 463–466. https://doi.org/10.1177/154193120504900353

Wickens, C. D. & Carswell, C. M. (1995). The proximity compatibility principle: Its psychological foundation and relevance to display design. *Human Factors*, *37*(3), 473-494. https://doi.org/10.1518/001872095779049408

Wickens, C.D., Dixon, S., & Seppelt, B.D. (2002). In vehicle display and control task interference (Technical Report No. ARLA2-7/NASA-02-5/GM-02-1). Savoy, IL: University of Illinois, Aviation Research Laboratory.

Yang, Y.Z., Wickens, C. Park, T., Siah, K., & Fong, L. (2015) Effects of information access cost and accountability on medical residents’ information retrieval strategy and performance during pre-handover preparation: evidence from interview and simulation study. *Human Factors, 57* 1459-1471.