DEVELOPING AND EVALUATING AN AUGMENTED REALITY INTERFACE TO ASSIST THE JOINT TACTICAL AIR CONTROLLER BY APPLYING HUMAN PERFORMANCE MODELS

Chris Wickens, Colorado State University, Gaia Dempsey, 7th Future, Andrew Pringle
Trinity College Dublin, Lucas Kazansky, DAQRI, Stefanie Hutka, Adobe Systems Inc

We developed a 3D augmented reality head mounted display (DARSADS-SVS HMD) interface to support the Joint Tactical Air Controller (JTAC). The JTAC's job is to integrate information about enemy attack units and nearby friendly forces and direct aircraft equipped with weapons to neutralize the enemy via close air support (CAS), while also safely routing air traffic. The JTAC's numerous and often overlapping tasks involve maintaining detailed situational awareness (SA) of a large quantity of information, and making rapid decisions that carry life-or-death consequences. Thus, the JTAC role requires many different cognitive operations across different mission phases. Designing an effective human-factored system that supports maximum SA while minimizing cognitive load required us to harness computational cognitive models of SA-supporting visual scanning, display layout, 3D frame-of-reference transformations, clutter, legibility and working memory. We applied such models to different phases of the JTAC mission (e.g., airspace management, call-for-fire), establishing a Figure of Merit (FOM) for each given design by summing FOMs across models, thus creating a mechanism to evaluate designs based upon their balanced impact on competing cognitive drivers. Models were differentially weighted for each phase, according to the relative importance of the relevant cognitive process to the phase in question. In this research paper, we illustrate two such design comparisons.

INTRODUCTION

The role of the Joint Tactical Air Controller (JTAC) is to coordinate close air support (CAS) on enemy positions that are threatening friendly and allied forces, and to safely direct air traffic within a given area of operation. As such, the JTAC has tremendous responsibility to assure the safety of these troops from both enemy fire and friendly fire, as the latter may result from misdirected weapons.

The information required to make these timely and accurate CAS decisions is vast and dynamic, and the outdoor environments in which JTACs must operate range from urban to rural, from day to night, and from mountainous terrain to desert.

As we describe below, the tasks required of the JTAC are also diverse, including maintaining 3D situational awareness of the dynamic battlefield environment and the related air space, visual search for potential targets, developing a spatial/temporal "game plan" of attack by multiple agents, weapons to target matching, target designation techniques, acting as air traffic control in coordinating flights to and around the battlefield, holding aircraft in a "stack" until the attack and then coordinating ingress and egress for the attack, communicating such information to friendly personnel, and evaluating the success of the attack with respect to the commander's intent. Each of these (and other) tasks, in turn requires a diverse arsenal of perceptual and cognitive functions such as visual search, information integration, planning, spatial cognition, decision making, working memory, and attention management.

The JTAC tasks are currently supported by a variety of non-integrated, often head down, information sources with little automation, such as binoculars, laser range finders, charts, note pads and radios; although an interactive Android-based tablet map of the battlefield is being adopted by USMC ground forces (KILSWITCH V2.5, 2016).

The goal of the research project described in this paper was to examine the feasibility of supporting the JTAC with an integrated Synthetic Vision System (SVS) in the form of an augmented reality (AR)-based head mounted display (HMD); a system we describe as the DARSADS SVS-HMD. As is well known from aviation and automotive engineering psychology research, the immediate benefit of a see-through display, such as a HUD or HMD is that it would support continuous head-up/eyes-out monitoring of the far domain while still allowing processing of the wealth of displayed information generated by the system (i.e., vehicle or, in the case of the JTAC, combat information; Wickens, Ververs & Fadden, 2004). A second benefit of a JTAC HMD is that combat information can be made accessible without impediments from disrupting environmental factors such as wind. A final factor that we exploit here is the use of AR or "conformal imagery" such that features on the display can overlay, identify or otherwise augment critical features in the environment, a feature with well-established benefits for the dismounted soldier (Yeh Merlo & Wickens, 2003; Wickens & Rose, 2001), as well as the pilot (Wickens et al., 2004). AR information displays have been shown to enable greater focus by minimizing gaze-switching between graphic or text information and the physical task at hand (Richardson et al., 2014). The aim of this research project was to design a methodology for AR interface design that would leverage these advantages, while also avoiding the potential cognitive and attention-management traps that can manifest in head-up-display interfaces, including attention tunneling and various

Copyright 2018 by Human Factors and Ergonomics Society. DOI 10.1177/1541931218621155

types of visual clutter that can reduce overall situational awareness and task effectiveness.

Our program of research involved two phases:

1. Generating Design Hypotheses: Using various human factors and cognitive engineering principles, we designed various iterations of the DARSADS-SVS HMD interface. In this approach, we adopted various “design philosophies” which generate specific design principles as described below.
2. Hypothesis Testing & Comparison: Evaluating prototype candidate designs of the system interface through an assembly of computational cognitive models, which we refer to as a “Super Model”.

Principles and Philosophy

We invoked several principles of design that may be described as “philosophies”, underlying the designs shown in Figure 1, which depicts the general format of the 20° x 30° HMD, viewed against terrain. This format is tailored, in the two figures, to illustrate its specific features for two of the 12 phases of CAS execution, as elaborated below.

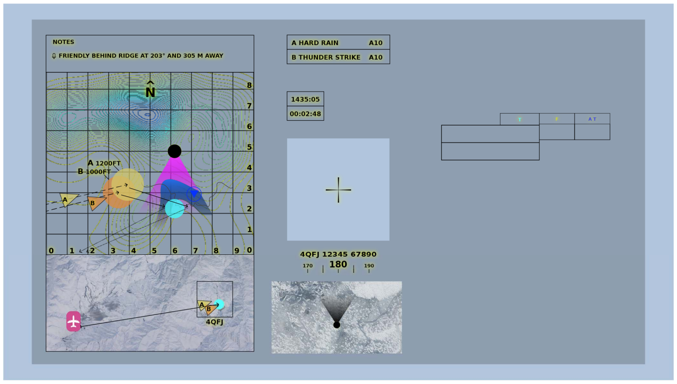

Fig 1a: Airspace Management Display. To portray the interface elements clearly, the background terrain has been removed.

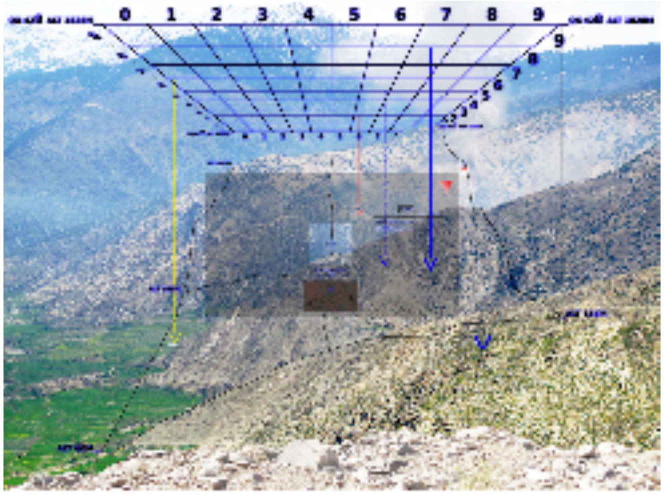

Figure 1b: Target Identification Display. The field of view of the HMD (shown in Figure 1a) is in the darker rectangle in the center through which the user can see the far domain terrain. If the head is tilted upward, the user can view the coordinates of the grid droplines, whose arrowhead terminations are to critical ground locations.

Following an extensive Cognitive Task Analysis (CTA), based on reviewing military handbooks (United States, 2014, Air Land, 2016) and consultations with subject matter experts who helped us identify critical tasks and information sources, and rate their relative importance, we gained an understanding of the 13, generally sequential but in some cases overlapping task phases in the JTAC mission, as shown in Table 1.

Table 1: 12 Phases pf CAS Execution

Phase Name	Description
1 – Routing / Safety of Flight	Routing and safety of aircraft within JTAC’s zone of operation. Ongoing task throughout mission. Related design candidate: **Airspace Management View, Fig 1a.**
2 – CAS Check-In	Communication with nearby aircraft about mission, number and type of aircraft, their position, altitude, ordnance, time on station, sensors, and capabilities.
3 – Situation Update	A tool used to increase SA regarding the tactical situation at hand. Involves acquiring latest information regarding targets, friendlies, threats, and communicating final attack considerations. Elements included are enemy activity, surface-to-air threat activity, friendly situation, remarks, weather and hazards. Related design candidate: **Target Identification Display, Fig 1b.**
4 –Game Plan	Planning attack heading, ingress point, and method of attack, and matching ordnance and sensors to target.
5-7 – CAS Brief, Remarks/Restrictions and Read Backs	Carefully scripted message of specifics of attack, including the 9-line and any relevant restrictions. This section also includes a Read Back procedure to ensure that all critical information sharedhas been correctly received.
8 – Correlation	As pilot flies to attack, assuring pilot sees the same target(s) as JTAC had designated, or in the case of distant targets, ensuring that aircrew takes responsibility for and has the information necessary to positively identify target(s).
9 – Attack	Throughout a CAS attack, the JTAC must maintain awareness to the aircraft position, the friendly situation, and the objective area.
10 – Assess Effects	Assess whether the commander’s desired effects were achieved. This assessment will determine whether to continue the attack, abort sequential attacks, or set up a reattack.
11 – Battle Damage Assessment	Accurate and timely BDA leads to a more accurate operational picture of the current enemy order of battle, which helps correctly dictate asset flow and allocation.
12 – Routing / Safety of Flight	More air traffic control. Related design candidate: **Airspace Management View, Fig 1a.**

Then, in developing our design for these different phases of the mission, we were guided by a series of general principles or philosophies of cognitive interface design developed over three decades of HUD human factors research conducted primarily in the context of air pilots, as follows:

Consistency. In spite of the differing information needs across phases, and the temptation to configure the interface display differently for each, we resisted this where possible, so that display elements on the HMD were located, as much as possible, in the same relative locations with the same layout for different phases (Andre & Wickens, 1992). Furthermore, the 12 CAS execution phases were grouped into 5 JADE (JTAC Augmented Dynamic Environment) modes, with the information for the different phases within a JADE mode (e.g., phases above 2-7) represented as close to identically as possible. The notable advantage of such consistency is the ability of the JTAC to locate information rapidly when under stress.

Situation Awareness Primacy. As noted, a major rationale for using a transparent optical display in the first place is to keep the far domain in view, as this is the sole source for noticing dynamic changes in information on the battlefield. But our design expanded upon this feature to include a "protected zone" in the middle of the HMD (see square with crosshair in figure 1) that is never obstructed by display imagery, other than a center reticle that can be used as a component of digital target designation (center the reticle on a target and "click").

Minimizing Scanning/Information Access Effort. Scanning is effortful, and head movements are more so (Wickens, 2014). Hence our goal was to keep most information relatively accessible either on the display itself, or just outside its perimeter, accessible then by a short head rotation to look at a body-referenced location (e.g., as if mounted to a tablet attached to the shoulder). The distance of information sources from the center of the field of view (the reticle) was generally made proportional to its frequency of use and importance (Wickens, Vincow et al., 1996).

The Proximity Compatibility Principle. We also endeavored to keep information sources that needed to be compared; such as a map and the forward view depicted in the map, or a commanded and actual aircraft altitude, as close together (proximate) as possible as dictated by the proximity compatibility principle (PCP: Wickens & Carswell, 1995; Wickens & McCarley, 2008). One direct derivative of the PCP is the use of AR or conformal imagery, which creates the closest proximity possible between display information and its counterpart in the far domain. AR has the significant advantage (over pure spatial proximity) of creating maximum proximity while minimizing visual clutter (see below). Examples of AR to create proximity are seen by the virtual grid, and the target cue arrows, pointing to ground targets in Figure 1b.

Maximizing Legibility: The Tradeoffs. One inevitable downside of superimposed imagery is the potential to mask information in the far domain by display symbology, and to mask information on the display, by far domain scenes of high visual density or spatial frequency. We refer to both of these clutter sources as "overlay clutter" (Wickens, Hollands et al., 2013). The first type of clutter is mitigated by the protected zone, but inevitable elsewhere across the display that may contain imagery. Furthermore, the close proximity of elements in a small space (i.e., small text designed to reduce overlay clutter) can create "density clutter" (Beck et al., 2010), by packing elements too closely together. Finally, both small display elements (i.e., reduced font and symbol size) and low intensity symbology (designed to reduce overlay clutter costs to the far domain), are the two elements most responsible for reduced legibility of critical display information (DOD 1472). Collectively these inevitable costs of superimposition, must be balanced against the HMD benefits of situation awareness and reduced information access effort noted above, and we focus a great deal of design and test attention on the quantitative tradeoffs between them, exploiting the "sweet spot" in the tradeoff where possible.

Frame-of-Reference Transformations (FORT). Much of the JTAC's operations require 3D spatial cognition: Where am I relative to my aircraft, and relative to the target? Where currently and where will the aircraft be relative to the target, to terrain hazards, to ground hazards such as surface-to-air missiles and to each other? Each of these spatio-geographical elements may be represented in a different frame of reference, and the transformations between these can create high workload and error (Wickens, Vincow & Yeh, 2005); hence we seek ways to minimize these transformations, with the prototypical example being to superimpose the 3D grid directly onto the forward view, via AR imagery in Figure 1b.

Minimizing Working Memory Load. In certain phases, (particularly 2-7) much of the JTAC's tasks involve communications, often of somewhat arbitrary digits, codes or acronyms indicating geographic position, weapon selection, or codes representing target designation information related to, for instance, laser designators or IR sparkle. We endeavor to reduce the vulnerabilities of confusion and memory failures, by support from the visual display of information to be communicated and received. This is accomplished via voice-to-text automation that displays the codes spoken by the JTAC visually within the display interface.

METHODS FOR EVALUATING DESIGNS

The value of computational human performance models in evaluation (Wickens & Sebok, 2014) is that they may be applied to design prototypes in advance of human-in-the-loop experiments (HITLs), weeding out clearly bad designs and highlighting a set of better designs (which then may be comparatively evaluated with HITLs). Such an approach can greatly reduce the cost of evaluation, involving multiple sessions or participants (in order to gain necessary statistical power) with highly paid, but scarcely available experts (to establish validity).

Our DARSADS-SVS HMD interface designs were subjected to model-based evaluation, whereby each principle was mapped to (typically) one existing, validated computational model, as shown in Table 2. Then the collective set of all models were applied to each JADE mode and then used to (a) derive an overall figure of merit (FOM) for the interface design in question to serve the relevant JADE; (b) in two instances, to compare separate design options for a given JADE phase, as we illustrate below.

Table 2: Method for Model-based Interface Comparisons.

	JADE Phase		
MODEL	**A**	**B**	**C**
Situation Awareness (Hooey et al., 1992)	M	M	L
Info. Access (SEEV Wickens & Sebok, 2014)	M	H	M
Prox. Compatibility (Wickens & Carswell, 1995)	M	H	M
Legibility: Contrast/Font (DOD 1472)	M	H	H
Legibility: Overlay Clutter (Beck et al., 2010)	M	H	H
Frame-of-Reference Transformation (Wickens et al., 2010)	L	H	L
Working Memory (cognitive effort)	M	M	H
Consistency (Andre & Wickens, 1992)	M	M	M
Sum of FOM across models			

Note: L= model is of Low importance for JADE phase, M= Medium importance for JADE phase, H= High importance for JADE phase. Info.= Information, Prox.= Proximity, FOM= Figure of merit. JADE A= airspace management, JADE B= target identification, JADE C= communicating game plan.

In our approach, for the two JADE modes shown in Figure 1 (for JADE A; airspace management and JADE B; target identification), we compared two interface design candidates to be described below. Such comparisons are of critical importance because any pair of designs will often trade off one principle – and thus one cognitive driver – against another (Wickens & Sebok, 2014). The most obvious example is that very close proximity in space (particularly overlay) will benefit ease of information access, but will penalize clutter legibility.

Each model is capable of producing a figure of merit or FOM (the complement of its maximum possible penalty (P) for "bad designs"). These FOMs can then be standardized relative to the maximum penalty by: FOM = 1- (P/Pmax) for each design. It is then possible to sum down the columns across all applicable models to compute an **overall FOM** for each design within a JADE mode in what we call a "Super Model". Such a sum can either be *unweighted* or *weighted* by the relative importance of the modeled cognitive process to the successful completion of the JTAC task at hand. As an example of weightings, communications (involving storage and processing of information in working memory and thus the working memory model) are extremely important for deriving and communicating the "Game Plan" to the air assets (JADE C) but less so for target identification (JADE B). Frame-of-Reference Transformation and far-domain situational awareness (SA) are very important for target identification, but less so for game plan communications.

RESULTS

JADE A: Airspace Management

Referring back to Figure 1a, we note the large map of the battlefield area on the upper left. This is a 2D top down map. We compared this with an alternative 3D rotatable (tilted) **perspective map** shown in Figure 2, a reasonable alternative since such a 3D exocentric perspective has been shown to be advantageous in maintaining overall 3D airspace and battle space awareness (Olmos Wickens & Chudy, 2000; Wickens Thomas & Young, 2001). (Figure 2 presents only the map itself, not other elements of the DARSADS-SVS HMD which are depicted in Figure 1a).

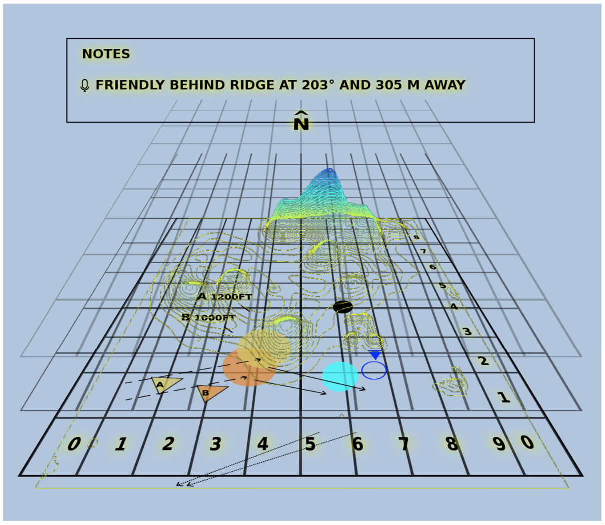

Figure 2: Three-dimensional rotatable map. Background is removed.

Table 3 presents the matrix described in Table 2, but this is now filled in showing the relative percent advantage (or cost) of the 3D map FOM over the 2D plan view map FOM for each model that is affected by the difference between the two formats.

Table 3: Results of the Super ModelCcomparison of Baseline Control vs Tilted Contour Map Airspace Management Design Candidates (JADE A)

MODEL	Tilted Contour Map Advantage	JADE Importance weight	Weighted ratio of FOM
Situation awareness	0%	0.5	0%
SEEV	0%	0.5	0%
Prox. compatibility	200%	0.5	100%
Contrast/font legibility	0%	0.5	0%
Overlay clutter	0%	0.5	0%
Frame of reference	50%	0.25	12.50%
Working memory	0%	0.5	0%
Consistency	0%	0.5	0%
Sum of FOM	**250%**		**112.50%**

The first data column presents the unweighted percent advantage yielded by applying the computational formulae to each design option. The second indicates our judgment of the relative importance of the model in question for this particular JADE, with weightings of 1, 0.5, and 0.25 assigned to high, medium, low importance respectively. As an example, Frame-of-Reference Transformation (FORT) plays a relatively lesser role for air-traffic management, since the location of the controller is not of great importance compared with the relative locations of aircraft, friendlies, and targets. The final column indicates this weighted ratio of the FOM favoring the design alternative relative to the baseline configuration. The bottom of this column portrays the 112.5% percentage advantage predicted for airspace management of the 3D rotatable map augmentation. Note that some of the models are silent regarding this map feature. For example, the overall layout of display elements does not change, so SEEV, which is heavily driven by the effort to move the eyes between display elements is unaffected (0% advantage). The two key models governing this advantage are PCP and FORT.

JADE B: Target Identification

Our second comparison was applied to JADE B, Target Identification, in which the JTAC must scan the environment and identify the nature and location of the target, expressed in grid coordinates. Here, as shown in Figure 1b, the JADE containing a 3D AR "grid", in which grid lines are directly presented in the sky above the ground, with drop lines to anything identified as a potential ground target or friendly unit, was contrasted with a baseline display without the grid. The model matrix comparison of the relative advantage of the augmentation is shown in Table 4.

Table 4: Results of the Super Model Comparison of Baseline Control vs 3D AR "Grid" Target Identification Design Candidates (JADE B)

MODEL	3D AR Grid Map Advantage	JADE Importance weight	Weighted ratio of FOM
Situation awareness	0%	0.5	0%
SEEV	16%	1	9%
Prox. compatibility	150%	1	300%
Contrast/font legibility	0%	1	0%
Overlay clutter	-50%	1	-50%
Frame of reference	200%	1	200%
Working memory	0%	0.5	0%
Consistency	0%	0.5	0%
Sum of FOM	**250%**		**458%**

In table 4, the column labels are identical to those of Table 3. We note here two features that differentiate the two display options. First, clutter is slightly increased by the AR grid lines, although this increase is not great because conformal imagery produces far less clutter than non-conformal imagery. Second, the proximity compatibility principle greatly rewards the AR grid lines because they place and indicate the 3D coordinates as directly connected to the target feature counterparts in the far domain. This advantage is also amplified because PCP (map-environmental comparisons) is highly relevant to the tasks in this phase, and because PCP is assumed to be the most important design feature overall (Andre & Wickens, 1992b). Hence, we note the very large predicted relative advantage of the AR grid over the control map.

DISCUSSION

In this research, we have shown how computational models of various cognitive and design factors can be aggregated into a Super Model, in order to produce a total Figure of Merit (FOM) for a design candidate in this vital, complex task. A legitimate criticism of this approach may be that several elements of this comparison are based on subjective factors, such as deciding upon the relative importance weights of different models (data columns 2 & 3) and hence the approach is not fundamentally different from an overall subjective evaluation of design options by a SME. (It is to be noted in this regard however that equal weighting models are often just as valid as those that are differentiated; Dawes, 1979). It is also important to acknowledge that the computational versions of some of these models (e.g., FORT) are less well validated than others (e.g., SEEV). For this reason, we strongly encourage further validation efforts to be undertaken in the form of HITL studies. We do believe that we have demonstrated the value of such an approach, for initial evaluation of complex systems involving highly skilled operators.

ACKNOWLEDGMENTS

This research was supported by a grant from the Office Of Naval Research, Grant # N68335-17-C-0290. Dr. Peter Squire was the technical point of contact, and we thank him and his team for their knowledgeable support.

REFERENCES

Air Land Sea Application (ALSA) Center. (2016). JFIRE: Multi-service tactics, and procedures for joint application of firepower.

Andre, A.D., & Wickens, C.D. (1992a). Compatibility and consistency in display-control systems: Implications for aircraft decision aid design. *Human Factors, 34*(6), 639-653.

Andre, A.D., & Wickens, C.D. (1992b). Layout analysis for cockpit display systems. *SID International Symposium Digest of Technical Papers*. Playa del Rey, CA: Society for Information Display

Beck, M.R., Lohrenz, M.C., & Trafton, J.G. (2010). Measuring search efficiency in complex visual search tasks: Global and local clutter. *Journal of Experimental Psychology: Applied, 16,* 238-250.

Dawes, R. (1979) The robust beauty of linear models. *American Psychologist*, *34,* 571-582.

Hooey, B. L., Gore, B. G et al (2010). Modeling Pilot Situation Awareness. In C. Cacciabue et al., (Ed.) *Human Modelling in Assisted Transportation*. Heidelberg: Springer.

Olmos, O., Wickens, C.D., & Chudy, A. (2000). Tactical displays for combat awareness: *The International Journal of Aviation Psychology, 10*(3), 247-271.

Richardson, Trevor; Gilbert, Stephen B.; Holub, Joseph; Thompson, Frederick; MacAllister, Anastacia; Radkowski, Rafael; Winer, Eliot; and Boeing Company, "Fusing Self-Reported and Sensor Data from Mixed-Reality Training" (2014). Industrial and Manufacturing Systems Engineering Conference Proceedings and Posters. 92.

US Defence Advanced Research Projects Agency (Darpa). (2015). *DPSS Kinetic Integration Lightweight SoftWare Individual Tactical Combat Handheld (KILSWITCH).*

US Department of Defense. (1999). Department of defense design criteria standard: Human engineering. Retrieved from http://everyspec.com/

United States Marine Corps. (2014). TACP: TACSOP. Retrieved from http://www.mawts.usmc.smil.mil/

United States Marine Corps. (2016). JFIRE. Retrieved from http://www.alsa.mil/mttps/jfire/

Wickens, C.D. (2014). Noticing events in the visual workplace: The SEEV and NSEEV models. In R. Hoffman & R. Parasuraman (Eds). Handbook of Applied Perception. Cambridge, U.K.: Cambridge University Press.

Wickens, C.D. (2014), Effort in human performance and decision making. *Human Factors, 56(8),* 1329-1336.

Wickens, C.D., & Carswell, C.M. (1995). The proximity compatibility principle. *Human Factors, 37*(3), 473-494.

Wickens, C.D., Hollands, J, Banbury, S. & Parasuraman, R.. (2013). *Engineering psychology and human performance* (4th ed.). Upper Saddle River, NJ:Pearson.

Wickens, C.D. Keller, J. & Small, R (2010) Development of the Frame of Reference Transformation Tool (FORT). *Proceedings of the 54th Annual meeting of Human Factors Society*. Santa Monica, CA: Human Factors.

Wickens, C.D. & McCarley, J.M. (2008). *Applied attention theory.* Boca-Raton, FL: CRC Press, Taylor & Francis.

Wickens, C. D., & Rose, P. N. (2001). *Human factors handbook for displays*: *Summary of findings from the Army Research Lab's Advanced Displays & Interactive Displays Federated Laboratory*. Thousand Oaks, CA: Rockwell Scientific Co.

Wickens, C. & Sebok, A. (2014). Flight deck models of workload and multi-tasking: An overview of validation. In M. Vidulich, et al. (Eds.). *Advances in Aviation Psychology: Volume 1*, pp 69-84. Dorset, UK: Dorset Press.

Wickens, C.D., Thomas, L.C., & Young, R. (2000). Frames of reference for display of battlefield terrain and enemy information:. *Human Factors, 42*(4), 660-675

Wickens, C. D., Ververs, P., & Fadden, S. (2004). Head-up display design. In D. Harris (Ed.), *Human factors for civil flight deck design* (pp. 103-140*)*. UK: Ashgate.

Wickens, C.D., Vincow, M.A., Schopper, A.W., & Lincoln, J.E. (1997). Computational models of human performance in the design and layout of controls and displays (*CSERIAC SOAR Report 97-22*). Wright Patterson Air Force Base, OH: Crew System Ergonomics Information Analysis Center.

Wickens, C. D., Vincow, M., & Yeh, M. (2005). Design applications of visual spatial thinking: The importance of frame of reference. In A. Miyaki & P. Shah (Eds.), *Handbook of visual spatial thinking*. Oxford University Press.

Yeh, M., Merlo, J.L., Wickens, C.D., & Brandenburg, D.L. (2003). Head up vs. head down: The costs of imprecision, unreliability, and visual clutter on cue effectiveness for display signaling. *Human Factors, 45*(3), 390-407.