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The Joint Tactical Air Controller: cognitive modeling and augmented reality HMD design.

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This paper describes the design and model based evaluation of DARSAD, an augmented reality head mounted display for the joint tactical air controller (JTAC), who manages and directs fire from air assets near the battlefield. Designs, based on 6 principles of attention, memory and information processing are produced for various phases of JTAC operations including target identification and airspace management. The different design candidates are evaluated and compared based on how they "scored" in adhering to model predictions, when those models were based on the above principles. Display designs, principles, models and the evaluation process are all described here.

The job of the joint tactical air controller (JTAC) near the battlefield 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 coordinating and routing air traffic (USMC, 2014; Wickens et al., 2018). Thus, a substantial portion of the JTAC's job resembles that of the air traffic controller in a highly unstructured airspace. Because the JTAC must operate in a mobile environment and often on foot, in order to support such multi-tasking and information integration, we harnessed the technology and principles of head-mounted display design from aviation rotorcraft operations (Wickens Ververs & Fadden, 2004). Furthermore, becaused of the geospatial environment in which the JTAC operates, and the need to identify and locate objects within that 3D space, we have exploited augmented reality (AR), in order to provide pointers to, or attach labels to, entities within that environment. Our system is labeled DAQRI Augmented Reality Synthetic advanced display, or DARSAD HMD.

Design

The challenge of designing the HMD for the JTAC is that the typical mission must proceed through most or all of 12 different phases. While these are described in detail in USMC (2014, 2016) and in Wickens et al., 2018, in brief, a higher level description of multiple phases involves:

- A. Identifying targets and their locations on the ground
- B. Bringing in air support from more distant bases and "stacking" them at the ready for attack (many similarities with air traffic control)
- C. Developing and communicating a "game plan" of attack, to friendly ground forces and air assets.
- D. Coordinating the actual air attack, assuring that the pilot is focused on the correct target(s)
- E. Assessing the results of the attack
- F. Routing air assets back toward their base.

Each phase has somewhat different information needs, some focusing on the battlefield, some on air assets, some on digital data bases, and some on various aspects of all three of these. Thus it is not appropriate to design a single "one size fits all" display; but neither is it optimal to design 12 different formats, each optimized for the task performed during the phase. Such a design will lack overall consistency, and can also lead to possible disorientation, with discrete switches of displays from one phase to another. Instead, our approach was to try to find a compromise between these two extremes, and hence provide visual momentum (Woods, 1984) between succesively viewed formats.

Shown in Figure 1, is the Display for initial (A) target selection, illustrating the momentary field of view occupied by the display, in the center, and the information in augmented reality i.e., the AR 3D grid structure that can be viewed by rotating the head. The natural terrain is visible behind, so as to superimpose the 20 X 30 degree FOV

HMD over a distant part of the visual field. This will be described in more detail below. Shown in Figure 2 is a zoom-in view of the display, in this case, specifically designed for (B) airspace management. The features of the display variations shown in Figures 1 and 2 will be described in greater detail later. However one key feature, in both, and all other display variations is the central rectangle in the middle. This is an unobstructed "no clutter" region designed to contain no added symbology, that supports the most sensitive possible view of the far domain, in order to support far domain situation awareness and high acuity target search and confirmation. The SA support region will be viewed when the eye is scanning straight ahead. A rotation of the eyeball of 2 degrees to either side, from this straight ahead axis will be sufficient to gain HMD-displayed information.

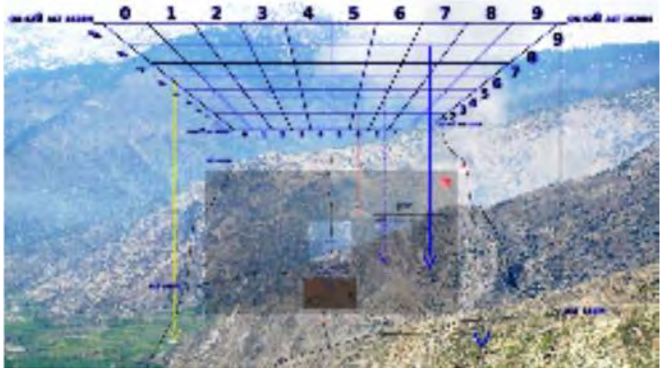
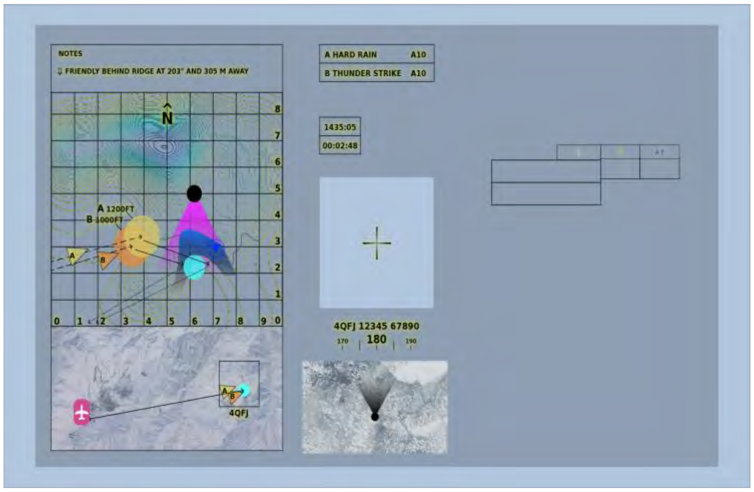


Figure 1. Example of the DARSAD HMD. The display itself is seen in the center rectangle, the grid imagery outside can be brought into view by head rotation. Vertical arrows point to ground location of targets (red arrows) or other entities. The AR gridlines in the actual display are rendered in low contrast white, to minimize clutter.



NOTES

FRIENDLY BEHIND RIDGE AT 203° AND 305 M AWAY

A HARD RAIN	A10
B THUNDER STRIKE	A10

1435:05

00:02:48

4QFJ 12345 67890

Figure 2. Airspace management design of the DARSAD. No far domain is visible. Note the no-clutter SA window in the middle. The three maps will be discussed below.

Our approach was twofold: (1) to design a single general format for a set of temporally adjacent phases; and to provide only minor modifications between phases within the set. For example item C in the bulleted list above, actually contains three of the 12 JTAC phases within it. (2) to endeavor to keep some general properties constant across all 12 phases (and hence all the different sets), in order to provide visual momentum. Thus it was necessary to design for the multiple tasks that must be performed by the JTAC, some concurrently (e.g., maintaining situation awareness of the battlefield, while communicating to air assets), and to consider the many different information processing demands of each task. Because of the multi-task nature of the DARSAD HMD, we chose to configure each display by adhering to multiple *principles* of display design, and then to evaluate a display's degree of adherence to the principle by a series of computational models, as described as follows.

1. *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 the "protected zone" in the middle of the HMD (see square with crosshair in figure 2) 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").

2. *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 visual angle distance of information sources from the center of the field of view (the reticle) was generally made proportional to its frequency of use and (Wickens, Vincow et al., 1997; Wickens, 2015).

3. *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 very use of AR or conformal imagery, which creates the closest proximity possible between display information and its counterpart in the far domain (Wickens & Ververs, 2004). 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 1.

4. *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 SA protected zone, but is 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 (US DOD 1999). Collectively these inevitable costs of superimposition, must be balanced against the HMD benefits to 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.

5. *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 are 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; Wickens Thomas & Young, 2000); 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 1. The costs of such transformations in 3D displays can be quantified via a computational model (Wickens Keller & Small, 2011).

6. *Minimizing Working Memory Load*. In certain phases, 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.

Model based Display Evaluation.

Each of the principles above were leveraged in designing DARSAD phase displays (our efforts focused primarily on designs for A,B and D). However the principles were again leveraged to perform relatively low cost *evaluation* of the suitability of different designs for each phase; a great service performed by computational models (Byrne & Pew, 2005). To accomplish this for each principle, we either derviced, or used an existing computational model of how the level of performance would be driven by principle-relevant factors in the design. As four examples:

1. A model of working memory would predict that the quality of performance is directly proportional to the number of items to be retained (between encoding and response: communications or entry into a keyboard) times the length of required retention.
2. Some clutter models already exist (Beck et al., 2010), and the quality of search and reading performance can be inversely and linearly related to the computed abount of displayed clutter.
3. The proximity compatibility model penalizes a dispalty directly proportional to the number of items that need to be integrated or compared, times the average spatial separation between the compared items. Note that this separation is, by definition, = 0 for comparing a far domain item with its AR-displayed counterpart in DARSAD e.g., comparing a far domain target with a circular surrounding cue.
4. The SA support model penalizes displays proportional to the distance of displayed information from the central SA-window, weighted by the frequency of use of such items.

Greater details of the computational elements of all six models can be found in Wickens et al., 2018, or by contacting the first author.

Given the tasks that are performed in a given phase, each of the seven models can then provide a “score” for the displayXtask combination within that phase revealing the extent to which the display design serves the task in question (if more than one task is performed within the phase, the score can be averaged for the model). Thus a given model could generated either a penalty or its complement, a “figure of merit” of how poorly (or well) the display design serves the principle in question.

In principle then, an overall phase-related figure of merit for a design could be derived by summing (or averaging) the model scores across the six models. We refer to this as a “meta-model”. One final step in this process is required however, because not all model principles apply equally to all phases. As an example, target identification (A above) places hevy demands on visual acuity through the SA window. So the SA model (Hooey et al., 2010) is quite relevant, but working memory considerably less so. In contrast, communications of an attack plan to ATC and to friendly ground troops places heavy demands on working memory (as do all communications; Morrow et al;, 2003), but far less on visual acuity and target search. Thus we add one more step of assigning an importance weighting (multiplier) of the degree of relevance of a model to a given phase. Here we chose three levels: 0. .5 and 1.0. From this we can create the figure of merit prediction of the weighted meta model.
With the above, we are equipped to derive a total figure of merit (FOM) to each designXphase combination.

However our interest was less in deriving an absolute FOM than it was in a *relative* FOM comparison between two display alternatives (e.g., AR versus non-AR presentation of geo-spatial information; or closely clustered versus more widely dispersed information). The reason that such comparisons are vital is because principles often trade-off against each other in design. For example a closely clustered display can impose penalties of clutter, but a widely dispersed one can impose penalties of information access and scanning. Computational models can inform the design/evaluation as to “who wins” a competition, for example between cluttered cluster display and the dispersed scan-intensive display, and by “how much”.

We report below, the results of two such comparisons of alternative prototypes for a given display. First, for airspace management (see Figure 1b), we compared a version with a 2D plan view situation map (the large map on the left side of Figure 2) with a 3D perspective map. Figure 3 presents schematics of the perspective map designs. We also note the other two maps in the display of Figuren 2. At the bottom left is the small scale map of routing from the base to the battlefield, only displayed for phases A and F. At the bottom center is a rotating map, always depicting the momentary view forward at the top, with the cone subtending the momentary field of view of the HMD (Aretz, 1991; Olmos Wickens & Chudy, 2000).

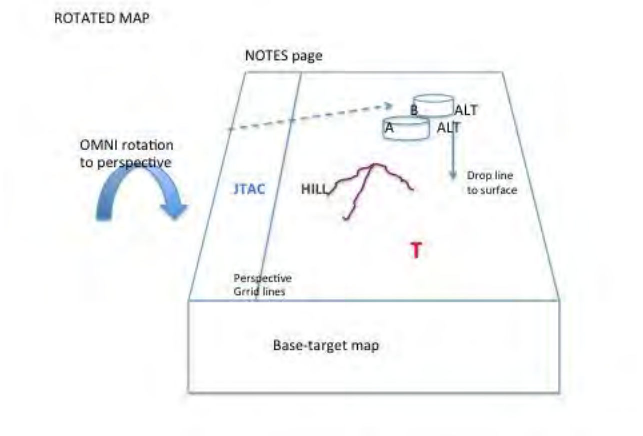


Figure 3. Schematic rendering of the 3D perspective version of the airspace management map Supporting phase B. The map can be rotated in depth, as shown by the blue arrow, to disambiguate distance and altitude of displayed aircraft, if required. The cylinders represent "stacks" where a given air asset may circle in a holding pattern.

Second, for target identification and acquisition, we compared the 3D AR grid rendering in Figure 1, with a second version in which there was no superimposed AR grid, where coordinates must be accessed from the screen perimeter. Figure 4 presents the two Tables in which the difference in six model scores, between the two designs are presented in the first column, the importance weights for each model are presented in the second, and the weighted model in the third. Shown in the bottom row is the meta-model score indicating the predicted percentage advantage of the candidate display (3D perspective airspace, gridline) over the less advanced display.

% advantage of 3D airspace map over 2D
For airspace management

Model	Importance weight of principle	% advantage
SEEV SA	.5	0
Proximity compatibility	.5	100
Legibility & contrast	.5	0
clutter	.5	0
Frame of reference	.25	12.5
Memory	.5	0
Meta-model		112.5%

% advantage of gridlines over no gridlines
for target ID phase

Model	Importance weight	% advantage
SEEV SA	.5	0
Prox compat	1	300
legibility	1	0
clutter	1	-50
Frame of reference	1	200
memory	.5	0
Meta model		450%

Figure 3: Relative percentage advantage of rotatable perspective airspace management display (left) and AR gridlines on target identification display (right).

The bottom line (literally and figurativerly) of Figure 4 is that in both cases, the more innovative display is predicted to have performance advantages and particularly so in the case of the AR gridlines. It is noteworthy in the latter case that there does exist a penalty for clutter; but this is more than offset by the AR benefit to proximity compatibility, as described above.

Conclusions and Limitatations.

The value of computational modeling for evaluation of display prototypes in the complex JTAC support system is demonstrated here. Of course the limitation of this research, at its current stage is evident: neither the individual models nor the meta-model are validated, either via performance or even subjective evaluation. It is our hope that such evaluation can be accomplished for the DARSAD-HMD, as well as an evaluation, through empirical validation, of the overall meta-modeling approach, to system evaluation.

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