Target Cuing in Visual Search: The Effects of Conformality and Display Location on the Allocation of Visual Attention

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Two experiments were performed to examine how frame of reference (world-referenced vs. screen-referenced) and target expectancy can modulate the effects of target cuing in directing attention for see-through helmet-mounted displays (HMDs). In the first experiment, the degree of world referencing was varied by the spatial accuracy of the cue; in the second, the degree of world referencing was varied more radically between a world-referenced HMD and a hand-held display. Participants were asked to detect, identify, and give azimuth information for targets hidden in terrain presented in the far domain (i.e., the world) while performing a monitoring task in the near domain (i.e., the display). The results of both experiments revealed a cost-benefit trade-off for cuing such that the presence of cuing aided the target detection task for expected targets but drew attention away from the presence of unexpected targets in the environment. Analyses support the observation that this effect can be mediated by the display: The world-referenced display reduced the cost of cognitive tunneling relative to the screen-referenced display in Experiment 1; this cost was further reduced in Experiment 2 when participants were using a hand-held display. Potential applications of this research include important design guidelines and specifications for automated target recognition systems as well as any terrain-and-targeting display system in which superimposed symbology is included, specifically in assessing the costs and benefits of attentional cuing and the means by which this information is displayed.

INTRODUCTION

See-through helmet-mounted displays (HMDs) allow a user to perform real-world tasks with a head-mounted guide – that is, information is presented in a way that overlays the user's forward field of view. For example, in the field of medical imaging, see-through HMDs allow doctors to view patient data in real time and superimpose data onto the patient (Azuma, 1997). Such displays have at least four apparent benefits: (a) the ability to operate in hostile or hazardous environments remotely (Drascic & Milgram, 1996); (b) hands-free operation for a mobile operator performing tasks requiring high information content (e.g., as an aid to maintenance engineers; Ockerman & Pritchett, 1998); (c) the ability to reduce scanning and, in particular, head movement while accessing information that would otherwise be presented in a head-down format; and (d) possibly using head tracking to capitalize on *world-referenced* imaging – that is, information that has direct spatially defined referents in the world beyond. Such imagery has sometimes been characterized as creating an augmented reality, in the sense that the far-domain imagery (reality) that is directly viewed is augmented by computer imagery that indicates or highlights particular locations, objects, or dimensions within that reality (Drascic & Milgram, 1996). For example, the user might see a pointer on the display designating the location of the target in the far domain.

However, these benefits must be weighed against the potential costs of using a see-through

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HMD: (a) The optics required for such a system are heavy and may impose a substantial amount of weight on the user's head; (b) the visibility of the far domain is reduced because of reduced light transmittance or a reduced field of view; (c) there is increased clutter in the forward field of view, such that in a worst-case scenario, the additional symbology in the near domain (i.e., the display) may obscure information in the real world (or far domain); and (d) there is a potential for *cognitive tunneling,* in which one domain captures attention so that events in the second domain are missed or ignored. Such tunneling may be induced not only by superimposing information at the same location (Fadden, Ververs, & Wickens, 1998; McCann, Foyle, & Johnston, 1992; National Research Council, 1997; Wickens & Long, 1995) but also by the use of world-referenced imagery because of its higher degree of apparent realism (Ververs & Wickens, 1998a).

This paper will address the latter two costs and the latter two benefits: the trade-off between the benefit of reduced scanning and the imposed cost of clutter, and the costs of cognitive tunneling induced not only by superimposed location but also potentially by world-referenced cuing.

Clutter-Scan Trade-Off

In the head-up display (HUD) domain, experimental evaluations have revealed a trade-off between two critical attentional variables: (a) the costs to focused attention when information is presented head-up so that it is superimposed on the outside scene, often creating a cluttered view, and (b) the benefits to divided attention, or information access, when head-up information is presented and the operator (pilot or driver) does not need to scan between the display and the outside world (Wickens, 1997; Wickens & Long, 1995).

Fadden et al. (1998) conducted a meta-analysis of research that has compared the presentation of head-up versus head-down information in the context of air and ground vehicles. The analysis revealed that the costs of scanning associated with head-down presentation generally outweigh the costs of clutter associated with head-up presentation, thereby generally favoring the latter (Fadden & Wickens, 1997; Martin-Emerson & Wickens, 1997; Ververs & Wickens, 1998b; Wickens & Long, 1995). However, such research also indicates that the clutter costs become greater and more disruptive as more information is added to the HUD (Ververs & Wickens, 1998b) and that these costs are also greater in detecting events in the far domain if those events are unexpected and not salient (Wickens, 1997). For example, Wickens and Long (1995) compared head-up (superimposed) versus head-down presentation of information to a pilot on final landing approach. The results showed that when pilots needed to focus attention on the far domain to detect runway incursions (an unexpected aircraft pulling onto the runway during the execution of a landing task), this detection was impaired by the increased clutter resulting from the head-up presentation of information.

The use of conformal imagery or augmented reality has helped to reduce the effects of the clutter-scan trade-off by explicitly directing attention to critical information in the real world (e.g., by superimposing a runway outline to direct the pilot's attention to the runway) when the user is performing tasks in which information from both near and far domains needs to be integrated (see Fadden et al., 1998, and Wickens, 1997, for summaries). For example, in an aviation flight simulation, Foyle, McCann, and Shelden (1995) and Levy, Foyle, and McCann (1998) found benefits for the presentation of conformal imagery when they asked participants to maintain their altitude and follow a ground path in conditions in which altitude information was superimposed either nonconformally or conformally along the flight path. Although nonconformal flight information improved performance on the altitude maintenance task, it resulted in poorer performance following the ground path; however, this trade-off was eliminated when the conformal displays were used, in which the altitude information was "scene-linked" to the lateral guidance cues.

The contrast between nonconformal and conformal imagery for HUDs has counterparts in the HMD domain: screen-referenced imagery, in which the displayed location of the information is based on a predetermined set of x and y display coordinates independent of head movement, and world-referenced or augmented reality, as described previously. Furthermore, world-referenced imagery can be divided into that which conforms to relatively enduring characteristics of the far-domain environment (e.g., a horizon line, a scale, or the contours of the terrain) and that which conforms to the location (or identity) of relatively transient entities within the far domain (e.g., a desired flight path, ground track, or, in the experiment we report here, a visual cue designed to direct attention to the estimated location of particular enemy targets). Such cuing can readily be presented head down as well as head up. However, in the head-down position, the cue appears less "natural" and direct and requires a greater degree of cognitive transformation to use in directing attention to a position in space.

Supporting this difference in cuing benefits between superimposed and nonsuperimposed locations, in HUD research we have found that the benefits of conformal cuing of enduring elements (locating the runway) are considerably enhanced when the cue is presented in a head-up rather than a head-down location (Fadden & Wickens, 1997; Wickens & Long, 1995). However, some evidence suggests that the compelling attention-guidance properties of the symbology may in fact exacerbate the cognitive tunneling costs; in other words, automation-based cuing or attentional direction may actually induce tunneling in non-HUD environments, as we discuss in the next section.

Cuing Effects: Directing Attention

It is relatively straightforward to predict that cuing a target location will facilitate the detection of that target (Flannagan, McAnally, Martin, Meehan, & Oldfield, 1998). Furthermore, extrapolating from basic research, one can predict that directly overlapping the cue on a target will provide faster and more accurate cuing than will a less direct means of guiding attention, such as an arrow pointing to the cue (Egeth & Yantis, 1997; Jonides, 1981; Muller & Rabbitt, 1989; Posner & Snyder, 1975). For example, Swennsen, Hessel, and Herman (1977) found that directing attention to the possible location of tumors on an x-ray plate led to enhanced detection of targets at that location. However, such cuing is likely to produce two sorts of costs. First, it may lead to a decreased response criterion at that location but not a gain in sensitivity (i.e., more hits but also more false alarms), a result that was obtained by Swennsen et al. (1977). Conejo and Wickens (1997) similarly found that cuing pilots of target location in an air-to-ground targeting task resulted in nontargets at that location being classified as targets.

Second, it is likely that directing attention to one location will decrease the likelihood that the user will attend to other locations and, hence, detect relevant events at those locations. This issue will be examined in the current experiments. Given that cuing can be viewed as a form of automation (the computer decides where a target is likely to be), this bias is a specific manifestation of the more general effect of automation-induced complacency, which has been observed in a variety of contexts (Mosier, Skitka, Heers, & Burdick, 1998; Parasuraman, Molloy, & Singh, 1993: Wickens, Mavor, Parasuraman, & McGee, 1998).

The findings that cuing benefits are enhanced with cues located close to (or superimposed over) the targets, relative to less direct means of attentional guidance (Jonides, 1981), suggests that cuing benefits will be greater with conformal (augmented reality) imagery. For example, the closer the cue is to the target, the more the user may trust the information provided by the automation and the more attention will be allocated to the region around the cue, consequently reducing the allocation of attention to the rest of the visual scene. Our interests are in whether such cuing costs will also be amplified by this conformal imagery. In the current experiments, we examine the costs of the second type described earlier – that is, whether valid cuing of moderate-priority targets will direct attention away from other tasks and targets of higher priority. Evidence suggesting that this might be the case is provided by a study by Ververs and Wickens (1998a), who found that a virtually conformal presentation of flight path guidance symbology on a HUD (i.e., symbology that moves in unison with its far domain counterpart but does not take on the same form or directly overlay it) caused a greater degree of cognitive tunneling than did a nonconformal HUD. They attributed this result to the compellingness of the display, which may have led pilots to rely solely on the symbology to perform their flight path maintenance task.

Thus although the results from the HUD literature suggest that the cost-benefit trade-off of cuing or attention guidance is mitigated when conformal symbology is used, this hypothesis has not been examined in the context of see-through HMDs. Despite the considerable amount of research on these devices (see National Research Council, 1997, and Yeh & Wickens, 1997, for reviews), little research has investigated the attentional framework trade-offs between near- and far-domain performance or how such trade-offs might be modified by the presence of augmented reality. One study of partial relevance was carried out by Sampson (1993). As participants walked on a treadmill performing an obstacle avoidance task, they were asked to respond to a reaction time task that required them to press a key on a numeric keypad when given instructions presented verbally (e.g., “northwest”), numerically, or spatially on a monocular, opaque HMD. The results showed that the participants took more time to complete tasks on the HMD when they needed to monitor for obstacles on the treadmill than when they were simply walking. Although the results implicate a cost for dual-task performance with overlapping imagery, they cannot reveal how much of that cost was attributable to the overlap. Furthermore, Sampson did not examine the effects of cuing or manipulate the referencing of the symbology.

More relevant is an experiment by Ockerman and Pritchett (1998), who examined the use of an HMD to assist in aircraft inspection. They found that inspection guidance on the HMD improved the detection of faults suggested by the computer-based advice on the HMD but also led to reduced detection of faults that were not suggested by the computer, relative to a control (non-HMD) condition. Furthermore, when a more “compelling” picture-based computer image was employed, more noncued faults were missed than when a text-based image was employed. Thus Ockerman and Pritchett’s results are also suggestive that HMD-based cuing could enhance attentional tunneling. However, their study was a preliminary one, with few inspectors per group, and unlike the current study, theirs did not employ direct conformal or world-referenced cuing.

The current study was designed to examine how the attentional costs and benefits of HMDs would be modulated by increasing the amount or degree of world-referencing and, in particular, conformal attentional cuing. In two experiments, participants viewed a virtual environment rendering of a far domain (mountainous topography) within which both cued and uncued military targets of either moderate or high importance were located (soldiers, tanks, mines, and high priority nuclear weapons). Their search for these targets was sometimes supported by valid attention cuing on the display; however, the high-priority targets were never cued. At the same time, participants performed a secondary task, rendered on the display. Thus the paradigm provided tasks of focused attention on information in the near domain (secondary task) and far domain (search for uncued targets) and of divided attention between the two domains (search for far-domain targets cued by near-domain symbology).

It should be noted that we considered the search for uncued targets and the secondary monitoring task to be focused attention tasks because they could be performed without referencing information in a second domain (e.g., the secondary task symbology displayed on the HMD was not relevant to the visual search task of locating objects in the far domain). That is, the paradigm required dividing attention between tasks, but the specific task itself required focusing attention on one domain or the other.

In Experiment 1 we employed a simulated HMD and varied the spatial accuracy of the target cuing by comparing world-referenced with screen-referenced imagery. In Experiment 2 we used a true HMD and compared the same world-referenced imagery of Experiment 1, and varied the degree of world referencing between a world-referenced HMD with a screen-referenced imagery positioned on a hand-held display.

EXPERIMENT 1: FRAME OF REFERENCE, CUING, AND VIEWING CONDITION

Methods

Participants. The 16 participants (12 men, 4 women) were paid $5.00/hr. Eight were civilian graduate students or staff at the University of Illinois and eight were U.S. Army personnel.

Environment. The experiment was conducted in an immersed virtual reality environment known as the CAVE Automatic Virtual Environment using head-tracked shutter glasses. The CAVE presented a 270° field of view surrounding the participant. The displays were created from static two-dimensional rendering of three-dimensional images depicting hilly terrain. Target stimuli consisting of tanks, soldiers, land mines, and nuclear devices were camouflaged in the terrain.

Displays. Figure 1 presents an example of the displays used for the experiment. The pictures show terrain and symbology presented on the center wall of the CAVE. Terrain depicted on the left and right walls are not included in this figure. Symbology was presented in green by the simulated HMD and superimposed onto the wall. The visual region of HMD-depicted information was 60° laterally by 60° vertically. This symbology was presented monoscopically to one eye or biocularly to both eyes; the far domain (terrain) was always visible to both eyes.

Heading was presented either nonconformally (i.e., screen-referenced, as shown in Figure 1), or conformally (i.e., world-referenced) with respect to the horizon line. The four cardinal directions were marked on each heading tape. Note that the heading tape displayed in the screen-referenced display was constantly present on the HMD in a predetermined location, whereas heading information in the world-referenced display was superimposed on the true horizon line, and as a result, the location of the heading tape on the HMD changed as the participant moved his or her head vertically in order to examine the environment.

Cuing symbology, presented for half the targets, consisted of an arrow pointing in the direction of the target object. In cued trials a cue was presented to signal the current lateral and vertical location of a target with respect to the participant's head orientation. For example, if the target was presented to the left of the participant, a left-pointing arrow appeared on the HMD as shown in Figure 1, indicating the presence and general direction of a target. Cuing information was presented with two levels of conformality: screen referenced or partially world referenced. In the screen-referenced display, the cuing arrow was located near the bottom of the display, three quarters of the way down from the top, indicating symbolically the direction of the target. The left-right direction of the arrow represented the side on which the cued target was located in relation to the participant. Its angle of inclination represented the approximate angle (above or below) the participant's horizontal line of sight in the visual field.

In the world-referenced display, a cuing arrow positioned on the perimeter of the screen display pointed directly toward the three-dimensional location of a target. In this example the arrow would indicate that the target was to the left and

(a) (b)

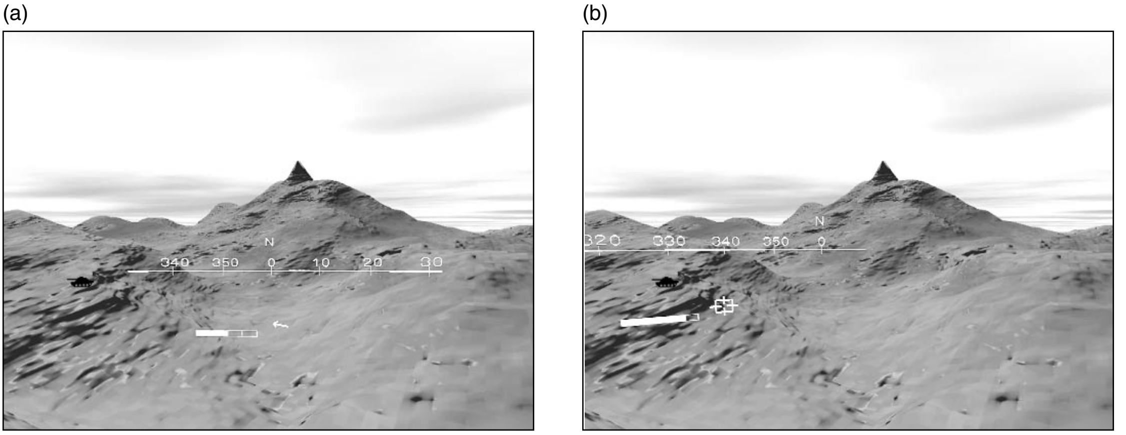

Figure 1. A tank may be seen in the left region of the terrain (symbology is described in the text). (a) Display symbology. (b) Lock-on reticle.

above. The cuing arrow could be positioned at the edges of the perimeter of a circle, the diameter of which subtended 40° of visual angle. In contrast to the screen-referenced arrow, the location of which was fixed, this arrow could move continuously as the participant's head orientation changed.

As shown in Figure lb, once the target was present in the forward field of view, the cuing arrow turned into a reticle (i.e., a box with four crosshairs). In the screen-referenced display, the cuing arrow was always in the center of the field of view and was not slaved in real time to head orientation; the reticle appeared in the same screen position as the cuing arrow. In the world-referenced configuration, the cuing arrow was presented along the periphery of a 40° field of view, always pointing directly toward the target, and the lock-on reticle was superimposed over the target once the latter was in the 40° field of view. A nuclear device was sometimes present in the environment as an "unexpected" high-priority target concurrently with either a cued or uncued target. Participants were instructed that reporting the nuclear device took precedence over the detection of all other targets.

Design. The experiment was a mixed design, as shown in Figure 2. The presentation of display (world referenced vs. screen referenced) was examined between subjects. Cuing (cued vs. uncued targets) and expectancy (nuclear devices vs. soldiers and tanks) was examined within subjects. We also manipulated viewing condition (monocular vs. biocular) within subjects by presenting the HMD symbology to either one eye or two; the far domain (terrain and target stimuli) was visible by both eyes projected on the screen beyond.

Six different terrains, created by taking static "pictures" from different locations from the U.S. Geological Survey database, were used in the experiment. For each viewing condition, participants were presented with 1 practice block (consisting of 10 search trials) and 10 experimental blocks; the latter contained a set of 20 search trials (6 each of tanks, soldiers, and land mines, and 2 nuclear devices). Half the tanks and half the soldiers were friendly (identified by their orientation: friendly targets faced toward the left), and the other half of each were enemies (facing toward the right). On half the trials, cuing was present (i.e., for all tanks and half of the mines). Only one expected

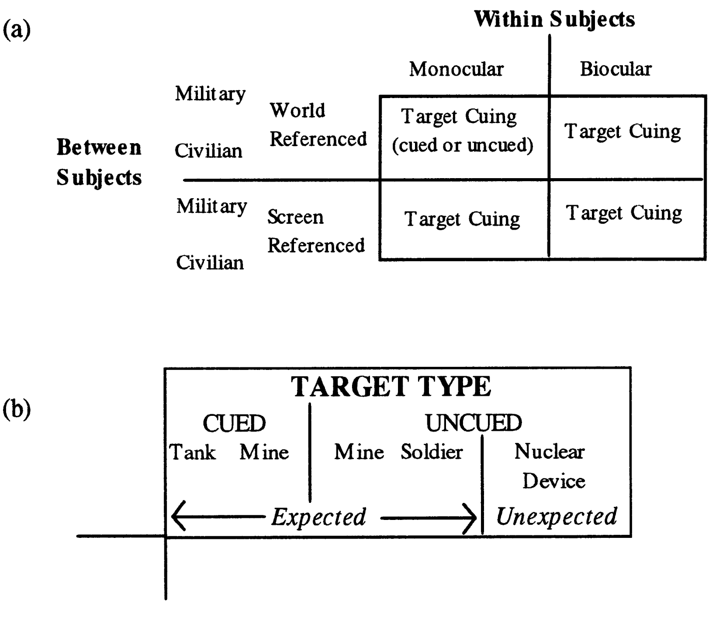

Figure 2. (a) Experiment design. (b) Expansion of each cell showing the different types and cuing of targets.

target was presented per trial, and participants searched until it was located. When present (one-ninth of the trials), the nuclear device was located within 15° of either a tank or a soldier. The nuclear device was never presented concurrently with the mine. The presence of cuing was randomized (i.e., unpredictable) over trials, as was the nature of the target.

Procedure. The experiment took approximately 2.5 h to complete, during which participants were given the instructions for the experiment and then performed the experiment. Participants were instructed to pretend that they were scouts sent to search for enemies and allies in unfamiliar territory. Their primary task was to find the targets, identify them as friend or foe, if relevant, and send information back to their troop regarding the objects' position. Their secondary task was to monitor an analog radio frequency display (shown at the bottom of the HMD in Figure 1), which provided data as to how close the enemy was in tracking their frequency. The solid bar gradually grew longer horizontally, filling in the rectangle from left to right at a variable rate between 2 and 4 s. When it passed the first marker, participants had 5 s to jam the enemy's frequency by responding with a button press. Responding before the solid bar passed the first marker had no effect. The secondary task continued until the target was detected.

Participants interacted with the display using a wand and shutter glasses – polarized lenses typically used to provide a stereoscopic view. The wand had three buttons and a pressure-sensitive joystick. Only the buttons were used during the experiment to make responses. The joystick was not used at all.

While searching for the target, participants responded to the secondary task by pressing the right wand button. To indicate that a target was detected, participants pressed the left button on the wand. The target identification task required participants to identify the target as friend or foe. Participants pressed the left button on the wand again if the target was foe, the center button if the target was friendly, or the right button in the case of a nuclear device. They did not need to identify whether the target was a tank, soldier, or land mine. Note that the button pressed for friend and foe identifications corresponded to the direction the object was pointing (e.g., participants pressed the left button if the tank or soldier was pointing left). Once the target was detected (land mine) or identified (tank, soldier, or nuclear device), participants orally reported its location by stating the target's bearing. Once the target was detected and reported, the display was darkened. When the participant's head was centered, a subsequent trial containing a new target was initiated.

After all targets were found within each 20-trial block, we measured participants' global awareness by asking them to describe the location of the targets within the environment to their commanding officer by selecting one of four ego-referenced pictures of the environment, one of which depicted the objects in the same location as in the environment they saw. Of the three incorrect pictures, one showed the tanks placed in different positions, another presented the soldiers in different locations, and the third depicted the land mines in incorrect sites. Not all the targets were presented. That is, targets presented on nuclear device trials were omitted from the pictures because it was not known which target the participants would detect in the nuclear device trials (i.e., would participants see the missile, or would the tank or soldier appearing with the missile capture their attention instead?).

Results

The total data set represented 10 dependent variables, consisting of response time and accuracy measures for the primary tasks of target detection, identification, and location; the frequency-jamming secondary task; and the global positioning recognition task. Because it was possible for participants to mistake a terrain feature for an object, trials with heading errors greater than ±20° were assumed to reflect these mistakes, scored as incorrect, and replaced with the participant's mean response time for like targets in that particular block (i.e., involving the same terrain) displayed on the same wall. This was approximately 5% of the trials. Additionally, outliers (4%) greater than ±3 standard deviations from the mean were replaced in the same way for response time data only. No accuracy data were replaced.

The results showed no difference attributable to participant population (army vs. civilian) on the target detection, identification, and location tasks. We found minor differences attributable to viewing condition (i.e., one eye vs. two eyes), but these results did not interact with our manipulation of cuing. Thus although these variables were included in the analyses we conducted, they will not be discussed in detail. (For more information, see Yeh, Wickens, & Seagull, 1998.)

Expectancy. A 2 (display referencing) × 2 (participant population: military vs. civilian) × 2 (viewing condition: one eye vs. two) × 4 (target type) within-subjects analysis of variance (ANOVA) was conducted on the response times and accuracy data for the detection of tanks (cued), soldiers (uncued), and nuclear devices. The nuclear device trials were separated into two classes based on whether the nuclear device was presented in the same visual search trial as a tank (cued) or with a soldier (uncued). Figure 3 presents the effects of display and target type on response time and accuracy. The bars in the figures indicate ±1 standard error from the mean.

In Figure 3 the filled symbols show responses when the uncued target (soldier) was present, the open symbols represent responses when the cued target (tank) was present, and the triangles represent the data points for the nuclear devices. The data showed no difference in detection times attributable to display referencing, $F(1, 12) = 0.06$, $p = .81$. The analysis revealed a main effect for target type, $F(3, 36) = 59.35$, $p = .0001$, such that the unexpected nuclear device when presented with a cued target was detected faster than when it was presented with an uncued target, $F(1, 12) = 37.86$, $p = .0001$. Additionally, the analysis revealed that the unexpected targets (nuclear devices) were detected faster than were the expected targets (tanks or soldiers) that appeared on the same trial: nuclear device on tank trial versus cued target (tank), $F(1, 12) = 14.02$, $p = .003$, nuclear device on soldier trial versus uncued target (soldier), $F(1, 12) = 12.92$, $p = .004$. Thus in terms of speed of response, participants adhered to the high prioritization of the unexpected nuclear device targets.

The effects of expectancy were manifested differently for accuracy and response time, as shown in Figure 3b. The data revealed a main effect of target type, $F(3, 36) = 113.55$, $p = .0001$, showing near-perfect detection accuracy for the two expected targets (tanks and soldiers), a level of accuracy that was substantially greater than for the unexpected targets (nuclear devices). For the latter, detection was more likely when it was paired with the uncued soldier (72%) than with the cued tank (53%), $F(1, 12) = 15.51$, $p = .002$. The data revealed no overall effect of display, $F(1, 12) = 0.78$, $p = .40$. However, analyses of the soldier trials showed an interaction that was attributable to better detection of nuclear devices in the world-referenced condition than in the screen-referenced condition, $F(1, 12) = 4.61$, $p = .05$. Despite the fact that nuclear devices on the tank trials (open

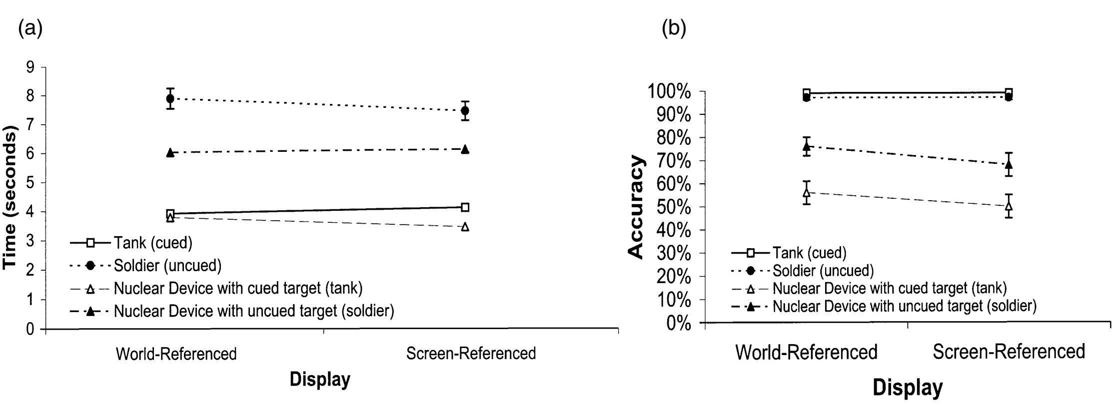

Figure 3. (a) Response time and (b) accuracy for expected and unexpected targets.

triangles) showed the same trend as the nuclear devices on the soldier trials, the effect here was not significant, $F(3, 36) = 1.12$, $p = .35$, presumably because of the greater variance in this within-subject comparison.

Cuing (mine detection). In the previous analysis, cued targets (tanks) and uncued targets (soldiers) differed not only in cuing but also in the shape of the target, which might have affected their visibility (although efforts were made to adjust image intensity so as to roughly equate visibility). Hence to determine the direct effects of cuing, unconfounded by differences in target type, we analyzed the cuing benefits for land mines, which were cued on half the trials. These data were analyzed using a 2 (display) × 2 (participant population) × 2 (cuing: cued vs. uncued) × 2 (eye) × 3 (wall: left, center, and right) within-subjects design. Analysis of target detection time showed a significant benefit of target cuing, $F(1, 12) = 194.27$, $p = .0001$, with cued mines being detected about 7 s faster than uncued mines (4.19 and 11.27 s, respectively). There was no effect of display, $F(1, 12) = 0.15$, $p = 0.70$, nor was the interaction between target cuing and display significant, $F(1, 12) = 2.76$, $p = .12$.

Analysis conducted on the accuracy data revealed no differences attributable to cuing, $F(1, 12) = 2.13$, $p = .17$, display, $F(1, 12) = 0.53$, $p = .48$, nor were there reliable interactions of Display × Cuing, $F(1, 12) = 0.53$, $p = .48$. The overall accuracy of mine detection was 99%.

Divided attention (secondary task). A 2 (display) × 2 (participant population) × 2 (eye) × 2 (cuing) ANOVA was conducted on the data for secondary task performance. In general, secondary task performance was uninfluenced by any of the experimental variables. The response time data showed no effect of display, $F(1, 12) = 0.46$, $p = .51$, or viewing condition, $F(1, 12) = 0.63$, $p = .44$, nor was the interaction between display and cuing significant, $F(1, 12) = 0.42$, $p = .53$. The secondary task accuracy data also revealed no effect of display, $F(1, 11) = 0.33$, $p = .58$, or viewing condition, $F(1, 12) = 0.00$, $p = .97$, nor an interaction between display and cuing, $F(1, 11) = 0.12$, $p = .73$.

Target identification. A 2 (display: world referenced vs. screen referenced) × 2 (participant population: military vs. civilian) between-subjects × 2 (viewing condition: one eye vs. two) × 2 (target type: tank, soldier) within-subjects ANOVA was conducted for the target identification task (i.e., report whether soldiers and tanks were friend or foe on the basis of their orientation). Results for the target identification task showed that friend-or-foe identification was 0.34 s faster with the screen-referenced display than with the world-referenced display, $F(1, 12) = 3.67$, $p = .08$. Participants were also more accurate in their identifications with the screen-referenced than with the world-referenced display, $F(1, 12) = 4.64$, $p = .05$. The interaction between the referencing of the display and cuing was not significant, $F(1, 12) = 0.09$, $p = .77$.

Target heading. Data for the target heading task were analyzed using a 2 (display) × 2 (participant population) between-subjects × 2 (viewing condition) × 4 (target type: tank, soldier, mine, and nuclear device) within-subject ANOVA. When determining the accuracy for the target heading task, errors in heading greater than 10° were considered incorrect. Heading information was given faster by participants using a screen-referenced display than by those using a world-referenced display, $F(1, 12) = 6.79$, $p = .03$. The target heading accuracy analysis showed no main effect of display, $F(1, 12) = 0.03$, $p = .87$, but a significant interaction between target type and display was present, $F(3, 36) = 5.39$, $p = .02$, such that heading accuracy for the three expected targets (tanks, soldiers, and land mines) was higher with the screen-referenced display than with the world-referenced display. However, the opposite was true for the unexpected target (nuclear device).

Global awareness. A 2 (display) × 2 (participant population) × 2 (viewing condition) × 5 (terrain) ANOVA was conducted on the accuracy for the global positioning task. The analysis showed no overall effect of display, $F(1, 141) = 0.17$, $p = .68$, but did show significant differences in performance attributable to participant population, $F(1, 141) = 6.41$, $p = 0.01$, in that military participants were more accurate in their responses than were the civilian participants. The interaction between display and participant population was not significant, $F(1, 141) = 1.14$, $p = .29$.

Discussion

The results revealed that cuing targets clearly assisted participants to detect them, and this benefit to divided attention was equally realized whether the cuing was world referenced (enabling a reticle to be placed over the target) or screen referenced (the reticle indicated that the target was within the field of view). Additionally, we observed a manifestation of cognitive tunneling reflected in a cost attributable to cuing for the detection of the simultaneous uncued target (the high-priority nuclear device). The data in Figure 3b clearly indicate that such a high-priority target was more likely to be overlooked if it appeared on the same trial with a cued tank than if it appeared with an uncued soldier. Hence, although divided attention between the near (cuing information) and far (cued target) domain was assisted by cuing, focused attention on the far domain was disrupted.

The data indicated, however, that the cost to detection of unexpected targets was reduced somewhat by the world referencing of the display (Figure 3b), an effect that was significant for uncued soldiers but not for cued tanks, although equal in magnitude for both. This effect parallels, to some extent, the findings of Wickens and Long (1995). By superimposing imagery with its far-domain counterpart (e.g., the horizon line) when the head is in motion, it can create a sense of fusion between the near and far domain, hence possibly *scene linking* (Foyle et al., 1996) the two domains in a way that would benefit attention to both. Wickens and Long (1995) found that cognitive tunneling costs for detecting unexpected events were reduced by world referencing (conformal symbology) of the imagery.

Although world referencing did provide the important benefit to detection of unexpected targets, it also imposed two noteworthy costs to performance. World referencing delayed the reporting of target azimuth, and the presence of the world-referenced reticle imposed a cost on classifying the target as friend or foe (i.e., discriminating left- from right-facing tanks and soldiers). The first of these effects can be readily explained by the fact that world referencing sometimes rendered the azimuth scale off the field of view of the HMD, if the head was oriented downward, hence requiring a short time to look up and bring the scale back into the field of view. The cause of the second effect remains somewhat obscure. When the imagery was world referenced, the cuing reticle would indeed partially mask the target, making its orientation difficult to ascertain. But the fact that the world referencing cost was also shown when the target was uncued (i.e., when masking was not observed) leaves this interpretation questionable.

EXPERIMENT 2: HEAD-UP VERSUS HEAD-DOWN DISPLAY

The results of Experiment 1 showed an overall benefit to target detection when the imagery was world referenced. There was also an overall benefit of target cuing (independent of the degree of conformality), such that a reticle pointing to the location of targets facilitated their detection. However, a somewhat disconcerting result was that cuing in particular imposed a *cost* on the detection of simultaneously viewable uncued targets of higher priority (the nuclear devices). This is attributable to a sort of cognitive tunneling, which could be the result of the very compelling nature of the cue. In directing the participants' attention to the cued location, the need to maintain a broader search to detect the infrequent (but highly important) target is disrupted.

Because we did not employ a head-down condition, the findings from the first experiment do not easily map onto the clutter-scan (focused-divided attention) trade-off underlying much HUD research (Wickens, 1997). Nor do the results address how such a trade-off may be moderated by features of the conformal (world-referenced) imagery in a way that might guide designers to present information that is most usable and least disruptive to soldiers' need to monitor the environment beyond. This was the goal of the second experiment: to compare performance using a head-up display and a head-down (hand-held) display. The paradigm employed in the second experiment was nearly identical to that employed in Experiment 1, except that the display manipulation was between a world-referenced HMD (increased clutter, reduced scan) and a screen-referenced hand-held display (reduced clutter, increased scan) and that an actual HMD was employed instead of a simulated one.

Methods

Participants. Eight U.S. Army personnel (Reserve Officers Training Corps cadets) at the University of Illinois at Urbana-Champaign participated in the experiment and were paid $5.00/h. None had participated in Experiment 1.

Environment. The experiment was conducted in the CAVE, as in Experiment 1, but rather than using the shutter glasses to simulate an HMD, we used a DataVisor VGA HMD for the experiment. The visual region of HMD-depicted information was only 25° laterally by 30° vertically (this contrasts with the 60° of symbology participants were presented with in Experiment 1). Although symbology was displayed monocularly to the participants' right eye, the field of view (i.e., the amount of information available to both eyes) was constrained to 30°. The 30° field of view presented to the participants was slightly less than the 40° available in night vision devices and significantly smaller than the 60° required by the U.S. Army for the Land Warrior System (National Research Council, 1997).

In the hand-held condition, participants viewed the image presented on a hand-held display with a 2.5-inch (6.35 cm) screen. They were required to wear head-tracked shutter glasses, which presented no imagery but reduced the visibility of the far domain to a level equal to the view through the HMD. The shutter glasses did not restrict the participants' field of view. The symbology on the hand-held display was visible to both eyes. A Flock of Birds head tracker (Ascension Technology Corp., Burlington, VT) was employed in both display conditions.

Displays. In the HMD condition, the lock-on reticle was displayed over the actual object. Because of variability in the head tracker attached to the HMD, the cuing was somewhat imprecise; thus the lock-on reticle could be slightly off target by approximately 0° to 3° in the *x* and *y* directions. The results of Experiment 1 showed no difference in cuing benefits between world-referenced and screen-referenced displays, suggesting that this imprecision would not create difficulties in target detection because, in this case, the target was within or close to foveal vision when the lock-on reticle was fixated. As in Experiment 1, the lock-on reticle was not used to signal the presence of any uncued targets that might appear in the participant's forward field of view.

An example of the hand-held display is presented in Figure 4. As Figure 4 shows, the hand-held display provided participants with a simple diagram of the world, heading information, cuing information, and the secondary task. The information on the hand-held display was presented nonconformally in a screen-referenced format – that is, if the participant moved the display in the environment, the positioning of the symbology (heading and cuing data) did not change. Representation of the walls of the CAVE (the lines at the edge of the display) were drawn in blue, and the heading information was presented in white against a black background.

In cued trials a cue was presented to signal the current lateral location of a target. This cue was independent of the participant's head or hand (display) orientation; in other words, the presentation of the cue did not change when the target was within the participant's field of view. Thus the world-referenced arrow, which in the head-up condition cued participants to the target's location, was not included in this display. The cuing reticle in the hand-held display did not indicate the elevation angle of the target.

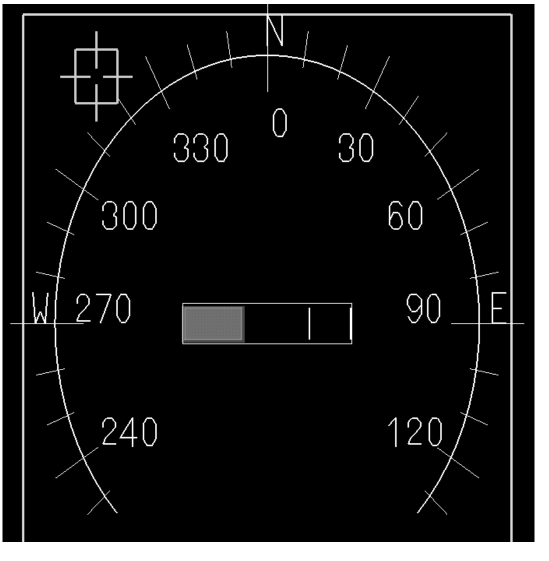

Figure 4. Hand-held display. The reticle at heading 315° indicates a cued target at that azimuth.

Tasks and procedures. The tasks and procedures in Experiment 2 were the same as those used in Experiment 1, except that we added an incentive based on secondary task performance: Participants were told they would be ranked based on their accuracy in performing the secondary task and could earn $40, $20, or $10 for first, second, or third place, respectively. To prevent participants from responding to the secondary task randomly (e.g., selecting the button every 3 s or so), participants were also told they would be penalized if they responded too early or too late. These instructions were designed to provide greater emphasis for the secondary task (and hence greater rationale for consulting the hand-held display). The secondary task was present on all trials.

Once participants found all the targets within each 20-trial block, they were shown four pictures of the terrain, identical to those used in Experiment 1, and selected which one depicted the objects in the same location as in the environment they saw. The pictures were always presented in an ego-referenced format.

Results

Approximately 5% of the trials were scored as incorrect and replaced with the participant's mean response time for like targets in that particular block (i.e., involving the same terrain) displayed on the same wall. Additionally, outliers (1% of the trials) greater than 3 standard deviations from the mean were replaced in the same way for response time data only. As in Experiment 1, no accuracy data were replaced.

Expectancy. A 2 (display: HMD vs. hand-held) × 4 (target type: expected and cued [tank], expected and uncued [soldier], unexpected with cued [nuclear device presented with a tank], unexpected with uncued [nuclear device presented with a soldier]) within-subject ANOVA was conducted on the accuracy and response times for the target detection task. Figure 5 presents the effects of display and target type on response time and accuracy. The bars in the figure indicate 1 standard error from the mean.

In the graph, the filled symbols are responses when the uncued target (soldier) was present, the open symbols represent responses when the cued target (tank) was present, and the triangles represent the data points for the nuclear devices. The main effect of display, $F(1, 14) = 11.46$, $p = .004$, suggested an advantage for the hand-held display, and the main effect of target type, $F(3, 42) = 29.12$, $p = .0001$, suggested that the most rapid responses occurred in cued trials (the open symbols). The significant interaction between display and target type, $F(3, 42) = 10.17$, $p = .0001$, suggests that the cuing effect was enhanced when the HMD was used and that the HMD cost was observed only on cued (i.e., tank) trials. Paired comparisons of the different target types revealed that as in Experiment 1, the unexpected but high-priority targets (nuclear devices) were detected faster than were the expected targets (tanks or soldiers) that appeared on the same trial: nuclear device on tank trial versus cued target (tank), $F(1, 14) = 14.07$, $p = .002$, nuclear device on

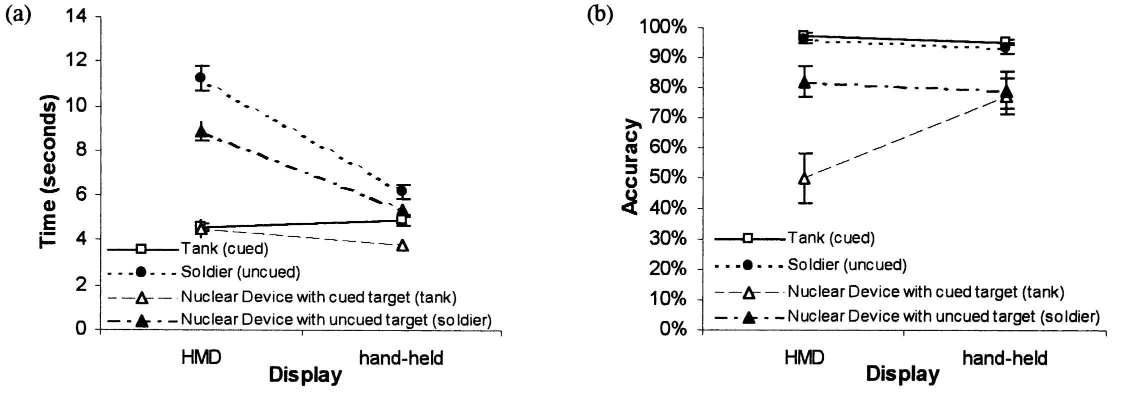

Figure 5. (a) Response time and (b) accuracy for expected and unexpected targets.

soldier trial versus uncued target (soldier), $F(1, 14) = 4.98$, $p = .04$. Thus the response time data show that participants adhered to the higher prioritization of the unexpected targets, similar to what was found in Experiment 1. As noted previously in discussing Figure 3 (Experiment 1), the apparent cuing advantage for tanks over soldiers (particularly with the HMD) is not examined statistically here because of possible confounds with target visibility. Cuing benefits will be described in the context of mine detection.

As shown in Figure 5b, the latency advantage for the nuclear weapons detection was purchased at a cost for accuracy, again replicating the effect observed in Experiment 1. The main effect of target type, $F(3, 42) = 9.54$, $p = .0001$, reflected this cost (a 25% reduction in hit rate for the nuclear weapons compared with near-perfect detection for the more expected soldiers and tanks). More specifically, the marginally significant Target × Display interaction, $F(3, 42) = 2.33$, $p = .08$, suggested that this cost was amplified only when the nuclear device was paired with a cued tank when using the HMD. Here accuracy plummeted to a mere 50%.

Cuing (mine detection). The data for detection of mines were analyzed using a 2 (display) × 2 (cuing: cued vs. uncued) × 3 (wall: left, center, and right) within-subject ANOVA. Figure 6 presents the effects of display on response time and accuracy. The bars in the figures indicate 1 standard error from the mean.

Data regarding mine detection showed a large response time benefit (5.78 s) for target cuing, $F(1, 14) = 33.37$, $p = .0001$. There was no effect of display, $F(1, 14) = 2.88$, $p = 0.11$, but a significant interaction between target cuing and display, $F(1, 14) = 11.38$, $p = .005$, indicated that the cuing benefit was enhanced in the HMD relative to the hand-held display.

Analysis conducted on the accuracy data also revealed an 8% benefit for cuing, $F(1, 14) = 24.54$, $p = .0002$. There was a marginally significant benefit for display, $F(1, 14) = 3.86$, $p = .07$, favoring the HMD. The interaction between cuing and display was not significant, $F(1, 14) = 1.08$, $p = .32$.

Divided attention between tasks. In order to determine how well participants were able to divide their attention between information presented in the display and information in the far domain, ANOVAs were conducted on the response time and accuracy data for the secondary task. A 2 (display) × 2 (cuing) × 2 (reward) ANOVA was conducted on the data for secondary task performance. The response time data showed no effect of display, $F(1, 14) = 0.21$, $p = .66$, or cuing, $F(1, 14) = 0.52$, $p = .48$, nor any interaction between cuing and display, $F(1, 14) = 0.72$, $p = .41$. The accuracy data also revealed no significant effect for display, $F(1, 14) = 2.45$, $p = .14$, or cuing, $F(1, 14) = 1.78$, $p = .20$, nor was the interaction between display and cuing significant, $F(1, 14) = 1.58$, $p = 0.22$. However, analysis revealed that false alarms (i.e., responding to the secondary task early) were greater during search for uncued targets (5%) rather than cued targets (2%), $F(1, 14) = 5.02$, $p = .04$.

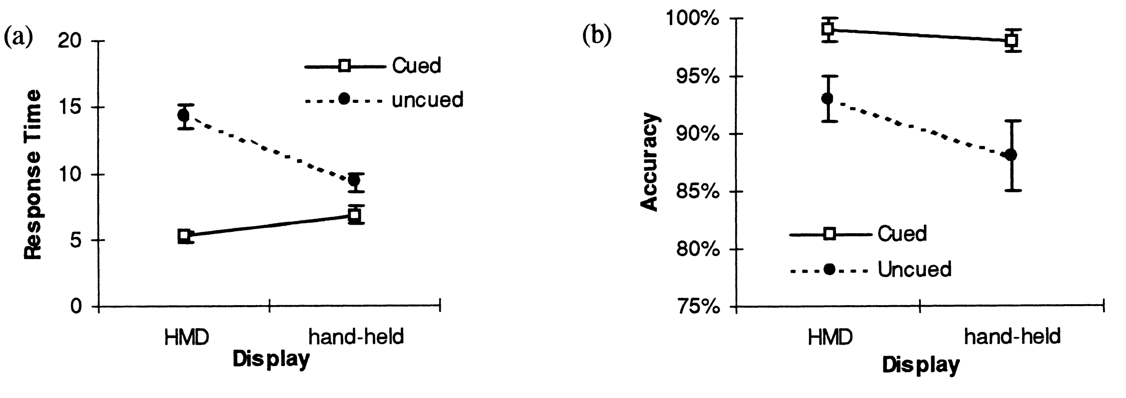

Figure 6. (a) Response time and (b) accuracy for mines.

Display effects for target identification and heading tasks. A 2 (display) × 2 (target type: tank, soldier) within-subject ANOVA was conducted for the target identification task. The results revealed no effect of display for either time, $F(1, 14) = 0.01$, $p = .94$, or accuracy, $F(1, 14) = 0.03$, $p = .86$.

Data for the target heading task were analyzed using a 2 (display) × 4 (target type: tank, soldier, mine, and nuclear device) within-subject ANOVA. When determining the accuracy for the target heading task, errors in heading greater than 10° were considered incorrect. A main effect of display on response times was observed such that participants gave heading information 1.37 s (48%) faster when using the HMD than when using the hand-held display, $F(1, 14) = 9.92$, $p = .007$. A main effect of target type was present, suggesting slower responses for the mines, $F(3, 42) = 4.60$, $p = .007$. However, an interaction between target type and display, $F(3, 42) = 2.89$, $p = .05$, suggested that this slowing was observed only with the HMD. The analysis of the accuracy data showed that performance with the HMD was 11.5% more accurate than with the hand-held display, $F(1, 14) = 27.11$, $p = .0001$. There was also a significant effect of target type, $F(3, 42) = 36.88$, $p = .0001$. The interaction between target type and display was not significant, $F(3, 42) = 0.96$, $p = .42$.

Global awareness. A 2 (display) × 5 (terrain) ANOVA was conducted on recognition accuracy for the global positioning task. The analysis showed an effect of display, $F(1, 77) = 7.06$, $p = .01$, such that participants' performance was better when they viewed the terrain with the HMD than when they used the hand-held display.

Scanning strategies. Analysis on participants' head motion along the *x, y,* and *z* axes was conducted using a 2 (display) × 4 (target type: tank, soldier, cued mines, and uncued mines) repeated-measures ANOVA. The data revealed that wearing an HMD constrained head movements; participants moved their head to scan the display significantly less in the *x, y,* and *z* directions when wearing the HMD than when using the hand-held display; *x* axis: $F(1, 14) = 28.41$, $p = .0001$; *y* axis: $F(1, 14) = 13.73$, $p = .002$; *z* axis: $F(1, 14) = 41.90$, $p = .0001$. That is, in the HMD condition, deviations from the head center point along the *x, y,* and *z* axes were approximately 46%, 54%, and 86%, respectively, less than their values in the hand-held display condition.

Discussion

The primary purpose of Experiment 2 was to compare the use of a world-referenced HMD with that of a hand-held display in a paradigm similar to that in which world- and screen-referenced imagery were compared in Experiment 1, thereby examining clutter-scan trade-offs that had been identified in the HUD literature (Fadden et al., 1998; Ververs & Wickens, 1998b; Wickens & Long, 1995). A secondary purpose was to reexamine the cuing effects that were observed in Experiment 1. In the following, we treat display location effects first before discussing the cuing effects.

Display location. Paralleling the findings from the HUD literature in the aviation domain, the current results suggest that in the performance of difficult tasks, trade-offs exist that are attributable to the possible operation of three factors. Two of these – clutter and scanning – are familiar from the HUD literature; the third, search strategy, appears to be unique to the HMD.

The most obvious benefit of HMD use is decreased scanning. This was evident through the response time advantage in reporting the target's azimuth, a benefit resulting from decreased scanning (i.e., from the horizon line to the target – both at a head-up display location in the HMD – versus from the target to the hand-held display). Surprisingly few other benefits for the HMD were found. Rather, we found a greater preponderance of costs. The costs were evident in the slower detection of uncued targets (soldiers and nuclear devices, as shown in Figure 5a), and in the decreased accuracy for detecting the unexpected nuclear devices (Figure 5b). Furthermore, no benefit for the near-domain secondary task was observed, whereas other studies in the HUD literature had found such a benefit (Foyle et al., 1995; Levy et al., 1998), suggesting here that the benefit might be offset by the HMD costs described earlier.

In interpreting the HMD costs, we consider first the familiar issue of clutter of overlapping imagery. The results suggest that presenting more information (e.g., the cuing or heading information) in the forward field of view, regardless of the degree of conformality, may have increased the difficulty in target detection. This HMD clutter hypothesis is based on previous findings regarding the problems of low salience in detecting rare events with the superimposed imagery, characteristic of head-up displays (Martin-Emerson & Wickens, 1997; Wickens & Long, 1995). More important, the presentation of cuing on the HMD had a significant and substantial cost relative to cuing on the hand-held display for the detection of the uncued low-expectancy but high-priority nuclear devices. This cost echoed a similar cuing HMD cost in Experiment 1. However, to the extent that clutter was responsible for the results, we might expect that the cost of clutter on the HMD would be enhanced by targets of low salience (the mines) and low expectancy (the nuclear devices) in relation to those of higher saliency and expectancy. The data only partially support this hypothesis. Detection times with the HMD were approximately 5 s slower than with the hand-held display for both the more salient soldier (Figure 5b) and the less salient land mine. It is important to note that there was no difference between the two displays in detection accuracy for the unexpected nuclear target in a low-clutter scene – that is, when no cuing information was present (soldier trials).

An alternative (but not mutually exclusive) hypothesis to the clutter hypothesis is that the HMD properties of a decreased field of view and greater physical weight altered the information-seeking strategies in a way that was detrimental to performance (Seagull & Gopher, 1997). We know because of the head movement data that search strategy was changed, and it appears to be changed in such a way that participants took longer to search for uncued targets with the HMD (e.g., the data for soldiers as shown in Figure 5a and for uncued mines). These data suggest that the search for targets with the HMD without cuing may be more careful, cautious, and systematic; whether this is because of decreased peripheral vision or greater effort of head movement, we cannot tell. Because of the greater effort of "free field scanning" and possibly because of restricted peripheral vision – a restriction that can hurt search (Hettinger, Nelson, & Haas, 1994) – it is therefore not surprising that the HMD benefited from target cuing far more than did the hand-held display. The relative benefits for cuing (the cuing benefit with the HMD minus cuing benefit with the hand-held display) was 0.98 s for the tank and 2.08 s for the cued land mines.

Thus the presentation of cuing information may have directed attention to a certain area of the visual scene, hence suppressing examination of the surrounding area when head movement in that examination was more difficult (as it was with the HMD). If this was the case, then the cost of detecting the unexpected targets using the HMD, relative to the head-down display, would be present only if cuing was also present. The accuracy data presented in Figure 5b support this hypothesis. That is, the augmented reality cuing in the HMD induces a sort of cognitive tunneling that is reduced when cuing is presented in its less "real" form on the hand-held display.

The hypothesis set forth was also true in Experiment 1, but the effect was even more pronounced in Experiment 2 (a 40% drop in the detection of the cued unexpected target, as shown in Figure 5, compared with a 10%–15% drop in Experiment 1, as shown in Figure 3), suggesting that in Experiment 2, the added cost of a physical HMD with a limited field of view (i.e., the increased effort of scanning, attributable to increased weight and limited field of view), led to a more restricted search and more reliance on the cue. In contrast, when using the hand-held display, participants were directed only to the general location of the target and thus were more likely to search a wider area around the cued target and detect the unexpected target. Note that the limited field of view with the HMD cannot account for participants' failure to detect the nuclear devices: The nuclear device was always presented within 15° of the target (tank or soldier), so the field of view was large enough that the nuclear devices were in the field of view when a cued tank was foveated. Furthermore, we would have expected a reduction in nuclear device detection for both cued and uncued HMD trials – as noted, however, only the former was seen.

The results for the global posttask recognition task suggest that display location (i.e., how the environment is viewed) may influence participants' mental representations of the location of objects in the environment. Accuracy on this task was poor with both displays; participants were correct 50% of the time when using the HMD compared with 30% for the hand-held display; chance performance was 25%. The results reveal the problems in using long-term memory to recall what participants may have considered incidental information, as found by Wickens, Liang, Prevett, and Olmos (1996). Our results on this task are inconsistent with previous research that has shown that a reduced field of view impairs one's ability to form a coherent representation of the world, given that context, which is necessary for accurate recognition, is lost (National Research Council, 1997). One factor that may account for our findings of an HMD benefit in scene recognition is the similarity of the physical format of the pictures to the environment in the HMD condition. Although participants using the hand-held display were also provided with this immersed view, attention was also shared with the hand-held display, which presented an egocentric, top-down view of the environment. These unexpected findings need to be examined further.

Cuing. We have already discussed how cuing produces a cost-benefit trade-off that is greatly amplified in the HMD compared with the hand-held display. In general, the presentation of cuing information reduced the search space, making the target detection task less daunting, but such benefits were modulated by the location of this information. Although targets were detected faster when participants used the hand-held display rather than the HMD, this benefit was limited to those instances when the targets were uncued, as shown by the analysis conducted on the data for land mine detection. That is, when targets were cued (e.g., the land mines), there was little difference in detection times attributable to the type of display. As noted, such cuing produced a cost for concurrently visible uncued targets.

Divided attention between tasks. The reduction of secondary task false alarms, produced by the primary task of detecting cued targets, seems to have been accompanied by a slight (though nonsignificant) increase in misses when the cuing was presented in the hand-held display. In the context of signal detection theory, these two changes suggest no overall change in sensitivity attributable to cuing, although they indicate a possible shift in response bias (such that the participant becomes more conservative) when cuing is present.

GENERAL DISCUSSION

The two experiments were conducted to determine whether manipulations of helmet-mounted and hand-held display design could aid tasks of focused attention in the near and far domains as well as divided attention between the two. Our most prominent finding was the cost-benefit trade-off imposed by cuing when using an HMD. Although cuing targets assisted their detection, both experiments showed its detrimental effect of participants' attention being directed away from, and therefore overlooking, the unexpected but high-priority target. This effect was replicated using a simulated (Experiment 1) and real (Experiment 2) HMD and by using different participant populations (military and civilian). Such a disruption could have serious implications and is reminiscent of the similar disruption of unexpected target detection caused by a head-up display (Wickens & Long, 1995).

Because the cuing was 100% reliable, we had no direct way of examining the extent to which automation-based cuing or highlighting could lead the soldier down the "garden path" of following the cuing even when it was in error (Swennsen et al., 1977). However, such an examination of cue validity was conducted by Conejo and Wickens (1997) using an air-to-ground attack simulation. Their results showed that even when information in the environment contradicted the information provided by the automation-based cuing, the pilots trusted and followed the automation. That is, despite trials when automation cued an incorrect target (or no target), the pilot still allocated less visual attention to analyzing the location of other objects in the environment when the true target was away from the unreliable cue or to analyzing the presence of objects in the environment in order to determine that no target was present. Their findings in the aviation domain and ours in the HMD domain suggest that the presence of cuing may result in an inappropriate allocation of attention: an overreliance on an automation-based cue. Similar conclusions regarding unreliable automation-based attention directions were derived from the research of Mosier et al. (1998) and Ockerman and Pritchett (1998). Furthermore, such a cost may be amplified as the realism of the cue increases (e.g., as in Experiment 2, in which head-up confomal symbology representing the target's location impaired detection of the unexpected target relative to the head-down – and less real – nonconformal symbology).

The data from Experiment 2 also revealed clutter-scan trade-offs between the use of a hand-held display and HMD. Benefits attributable to reduced clutter in the forward field of view can account for the hand-held advantage in speed of target detection and the accuracy with which unexpected events were noticed. However, using the HMD eliminated the scanning and accommodation that otherwise were necessary to reallocate attention between data presented in the near domain and objects in the far domain, leading to a benefit for the HMD over the hand-held display for the target azimuth reporting task. Note that some amount of visual scanning was required by participants when using either the HMD or hand-held display, but the data suggest that the cost (distance) of head-down scanning for the hand-held display was greater than the cost of upward scanning to the HMD horizon line, where the heading information was conformally located. Additionally, because the hand-held display was closer than the far domain to the participant, visual accommodation was necessary to bring information in either domain into focus. With the HMD, however, information was presented at the same distance as objects in the far domain.

The paradigm that we used to evaluate the simulated HMD appears to offer promise for further use. The tasks appeared challenging, as witnessed by the substantial time delays involved in target detection, ranging from 5 to 15 s. Furthermore, mimicking the search for targets in the real world (Wickens, 1992), it is noteworthy that on a number of occasions the target passed through the field of view without being detected. However, the nature of our findings, and the extent to which they are generalizable, may be limited both by the experimental constraints of the stimuli we presented and by the hardware we used. Our target stimuli (tanks, soldiers, land mines, and nuclear devices) were physically different and subtended different degrees of visual angle. Consequently, one explanation for the greater misses in unexpected event detection when the nuclear device was paired with the tank, compared with when it was paired with the soldier, may be attributable simply to the fact that the tank was easier to see than the soldier or nuclear device, and not because the tank was cued. To compensate for these differences, we made contrast adjustments to ensure that the uncued targets were a bit more salient than the cued targets and that the unexpected targets (nuclear devices) were more salient than the expected targets. Participants were also instructed that the nuclear devices were of higher priority.

However, we cannot ignore the differences in the field of view and in the weight of the devices in Experiment 2 in our comparison of the HMD with the hand-held display. Both these factors may have contributed to the head-down display benefit but would nevertheless be present in the real world of the soldier. The reduced field of view prevented the participant from accessing information in the periphery, which may have hindered the visual search task. This factor alone could have been overcome by increased scanning, but the weight of the HMD may have prevented the participant from even attempting to completely scan the environment. Thus we acknowledge that the benefits we found for the hand-held display in Experiment 2 may be reduced if either the weight or the reduced field-of-view factor were eliminated.

CONCLUSION

The current results reveal that the cost-benefit clutter-scan trade-off can be modified or modulated by the platform on which cuing is presented. The use of a hand-held display slightly reduced the benefits of cuing but greatly reduced the cost of cuing to the detection of concurrent uncued high-priority targets. The results of Experiment 2, in which a real HMD was used, suggest that these cuing costs may be amplified when the HMD is heavy, consequently limiting head movement, or when the field of view is significantly reduced. However, this large benefit attributable to the hand-held display (reducing the cost of unexpected target detection) was partially offset by a smaller cost in reporting the azimuth of targets (a cost attributed to scanning) and in recalling target locations (a cost of uncertain origin).

The possible benefits of cuing clearly depend heavily both on the reliability of the automation that imposes the cuing (in the experiments conducted, we employed the "best case" – i.e., perfect reliability) and on the costs of failing to detect uncued targets. These issues are the subjects of future research.

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