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# ATTENTIONAL LIMITATIONS WITH HEAD-UP DISPLAYS

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## ABSTRACT

Recent models of visual information processing suggest that visual attention can be focussed on either Head-Up Displays (HUD) or on the world beyond them, but not on both simultaneously. This hypothesis was tested in a part-task simulation in which subjects viewed a simulated approach to a runway with a HUD superimposed. An alphanumeric cue ("IFR" or "VFR") appeared on either the HUD or the runway and was followed by two sets of three geometric forms; one set on the HUD and one set on the runway. Each set contained one potential target, either a stop sign or a diamond. If the cue spelled "IFR", subjects made a speeded response based on the identity of the HUD target; if the cue spelled "VFR", subjects made a speeded response based on the identity of the runway target. Regardless of cue location (HUD or Runway), responses were faster when the cue and the relevant target were part of the same perceptual group (i.e., both on the HUD or both on the runway) than when they were part of different perceptual groups. These results, as well as others, suggest that attentional constraints place severe limits on the ability of pilots to process HUD-referenced information and world-referenced information simultaneously. In addition, they provide direct evidence that transitioning from processing HUD information to processing world information requires an attention shift. Implications for HUD design are considered.

## INTRODUCTION

HUDs consist of a combiner glass, superimposed between the pilot and the windshield, on which instrument symbology is projected. Although HUDs are becoming increasingly popular, important human factors issues have not yet been addressed. For example, it is widely assumed that placing instrument information in the forward field of view enhances a pilots ability to utilize both instrument information and environmental information simultaneously (Lauber, Bray, Harrison, Hemingway, & Scott, 1981). This ability is associated with clear operational advantages. FAA regulations mandate that pilots acquire enough visual information about the runway to determine whether to proceed with the landing, or initiate a go-around, by the moment they reach decision height. Pilots attempting low visibility landings have only a short period of time to extract visual information before making their decision. With conventional head-down displays, the time to transition from processing instrument information to processing out-the-world information is considerable, involving both eye and head movement time and reaccomodation time (Lauber, et al., 1981). If HUDs enable pilots to process instrument symbology and world-referenced information simultaneously, transition times would be abolished, yielding a significant operational advantage over conventional instrumentation.

From a human factors perspective, however, there may be problems with the parallel processing assumption. Models of visual/spatial attention typically assume that visual information processing proceeds in two stages. In the first, preattentive stage, complex visual scenes (such as those confronting pilots using HUDS) are parsed into groups of objects, where "group" is determined by Gestalt principles such as common color, common fate, etc. In the second, attended stage, perceptual groups are used to control the distribution of spatial attention across the visual field. Because visual/spatial attention is a limited resource, it can only be focussed on one group at a time (Treisman, 1982). This has two important consequences: first, parallel processing of objects in two perceptual groups is difficult to achieve, and second, transitioning from processing information in one perceptual group to processing information in another group requires a shift of spatial attention (Treisman, 1982).

At least three perceptual cues typically distinguish HUD symbology from the world (Foyle, Sanford, & McCann, 1991). Perhaps the most salient cue is differential motion: HUD's are stationary, whereas objects in the world follow trajectories through a common flow field (in addition, there is generally some vertical and lateral shearing of the "world" from variations in the aircraft's pitch and yaw). A second cue is color: HUDs are generally drawn in highly saturated green, whereas objects in the world come in various hues of various saturations. A third cue is perspective: Objects on the HUD are oriented vertically with respect to the eye plane, whereas scene-linked objects, including the runway and any forms on the surface of the runway, are rotated in the depth plane (a consequence of viewing the scene from above and behind).

Recent evidence (e.g., Baylis & Driver, 1992) suggests that color and motion are powerful determinants of perceptual grouping. Since these very cues (among others) distinguish HUDs from the world, the visual system is likely to parse the HUD as one perceptual group, and the world as another (Foyle, et al., 1991). It follows that when subjects are actively monitoring HUD symbology, visual/spatial attention ought to be captured by the HUD, leaving the world unattended. Consequently, objects in the world may not be processed in parallel with HUD symbology, and transitioning between the HUD and the world may be slowed by the requirement to shift attention between groups.

Previous work provides some support for these possibilities. Fisher, Haines, & Price (1980) found that when pilots used HUD symbology to perform a simulated landing onto a runway, they frequently failed to notice runway incursions; indeed, these failures were more prevalent among pilots using HUDs than among pilots using a head-down ILS system. This result is consistent with the assumption that when attention is focussed on the HUD, objects in the world do not reach awareness (see also Neisser & Becklen, 1975). Larish and Wickens (1991) recently developed a part-task simulation where pilots are in control of a descent through a series of cloud banks. When the aircraft is in the cloud bank, the world is invisible; during these periods, pilots are presumed to be attending to the flight relevant information on the HUD. As soon as the plane emerges from the cloud bank, the runway becomes visible. In one relevant study, pilots were instructed to make a speeded response based on whether a signal adjacent to the runway was red or yellow, every time they emerged from a cloud bank. Response latencies averaged over 1.5 s.

These response latencies are more than a second slower than in other color discrimination experiments (Fagot & Pashler, 1992). According to Larish and Wickens, "the response time to this signal provided a measure of the subjects' speed of switching attention from the instrumentation to the far domain" (p. 16). However, it is not clear whether visual attention switching was the critical factor producing the long response times in the study. The result was obtained in a multi-tasking situation; subjects were monitoring and responding to flight-relevant symbology on the HUD in order to maintain their approach, and the color-discrimination task was embedded in this ongoing activity at unpredictable intervals. The slow reaction times to perform the color discrimination may have been caused by delays in noticing the stimuli, response conflicts with concurrent tasks, or other factors.

## ISOLATING EFFECTS OF ATTENTION

The present paper had two goals. The first goal was to test the hypothesis that the visual system parses HUDs and the world as separate perceptual groups, so that when attention is focussed on the HUD (world), objects in the world (HUD) are excluded from processing (Foyle, et al., 1991). The second goal was to determine whether transitioning from the HUD to the world (and from the world to the HUD) requires a shift of attention. Each trial involved a low fidelity simulated approach to a runway; because the stimuli were presented against a dark background, the approach had the appearance of taking place at night under clear visibility (see Figure 1). The primary stimuli included a Head-Up Display (HUD), consisting of four boxes and two sets of pitch lines, and the surface of a runway. The HUD was drawn in light blue, the runway in light yellow. Following Weintraub, Haines, & Randle (1984), subjects began each trial by monitoring either the HUD or the runway for the appearance of a three-letter cue, either "IFR" or "VFR". Shortly after the appearance of the cue, two sets of 3 geometric symbols were added to the display. One set was distributed across the HUD boxes, and the other set was distributed across the surface of the runway. One of the symbols in each set was a potential target, either a diamond or a stop sign. If the cue spelled "IFR" (for instrument flight rules), the set of geometric symbols on the HUD was deemed relevant, and the set on the runway was deemed irrelevant. If the cue spelled "VFR" (for visual flight rules), the runway set was deemed relevant, and the HUD set was deemed irrelevant. Subjects searched the relevant set of symbols for the target; they pressed one button if they identified a stop sign, another if they identified a diamond.

Figure 1. Example of a between-group trial (see text). The VFR cue occupies the lower left box of the HUD; the relevant target (a diamond) occupies the lower left location on the runway. Subjects first identify the cue (VFR), which alerts them to search for and identify the diamond on the runway.

This procedure yields two kinds of trials. Intra-group trials are those where post-cue processing (i.e., visual search and target identification) is logically confined to stimuli belonging to the same perceptual group as the cue. An example of an intra-group trial would be when an "IFR" cue appears on the HUD. Inter-group trials are those where post-cue processing is logically confined to stimuli belonging to the other perceptual group (as in Figure 1, where "VFR" appears on the HUD). Comparing performance in the two trial types provides a straightforward test of the attention-switching hypothesis. That is, the initial requirement to identify the cue should cause attention to be focussed on the perceptual group containing the cue. If processing objects in the other group requires an attention shift, responses on inter-group trials should be slower than responses on intra-group trials. On the other hand, if attention shifting is not required (either because the visual system does not parse the visual field into groups, or because perceptual groups are not the units of attentional allocation), there should be no difference between the two kinds of trials.

In addition, the presence of a potential target (stop sign or diamond) in both the HUD group and the runway group provides a test of the hypothesis that when attention is directed to one group, objects in the other group are excluded from processing. Previous research (Eriksen & Eriksen, 1974) has shown that a nontarget stimulus facilitates responses to the target if the target and nontarget are associated with the same response (as in Figure 1, where both the target and nontarget are diamonds). Similarly, a nontarget stimulus interferes with responses to the target if the target and nontarget are associated with different responses (as when the target is a stop sign and the nontarget is a diamond). However, these congruency effects are eliminated if the nontarget is fully unattended (Yantis & Johnston, 1990). If attention is fully captured by either the HUD or the world grouping, therefore, congruency effects should be smaller on intra-group trials (where the nontarget belongs to a perceptual group that is never attended) than on inter-group trials (where the nontarget belongs to a perceptual group that is initially attended).

## METHOD

Subjects. The subjects were 20 undergraduates from San Jose State University. All subjects reported normal or corrected-to-normal vision.

Apparatus and stimuli. The experiment was run on a personal computer equipped with an Intel 486 processor. All aspects of stimulus presentation and data collection were controlled by the computer.

Stimuli were presented on a CRT screen. The "world" consisted of a horizon line extending across the screen (14 cm from the bottom of the screen), and a rectangular outline (runway) with a broken line down the middle. At stimulus onset, the runway measured 1 cm wide on the side farthest from the viewer and 23 cm wide on the side closest to the viewer. Superimposed on the world stimuli was a HUD, consisting of "pitch" lines, four small rectangles (two on the left and two on the right), and an airplane symbol (see Figure 1). The rectangles measured 1.9 cm in width and 1.1 cm in height. The vertical separation between top and bottom rectangles was .6 cm, and the horizontal separation was 5.4 cm. The HUD remained stationary throughout the trial.

The experimental stimuli consisted of a three-letter cue, either IFR or VFR, and two sets of three geometric symbols. One of the symbols in each set was either a stop sign or a diamond, and the other two symbols were a triangle and a square. The HUD set were imbedded within three of the four HUD boxes. When the cue appeared on the HUD, it filled the fourth box, either the bottom left or the bottom right. The runway set was located in three of four analogous locations directly below the HUD. When the cue appeared on the runway, it appeared in the fourth such location, either the top right or the top left. Consistent with the constraints imposed by the fact that the runway was changing constantly, careful efforts were made to ensure that the physical distances between the HUD stimuli and the runway stimuli, and the physical sizes of the two sets of stimuli, were approximately equated.

<u>Motion</u>. To simulate motion, the shape of the runway was modified at a rate of 12 hz, making it appear as if the subject was on final approach. In addition, small vertical and lateral displacements were superimposed on the descent, simulating changes in the aircraft's pitch and yaw induced by minor buffeting. It took approximately 5 sec to make contact with the surface of the runway, considerably longer than subjects typically required to make their response.

<u>Design</u>. The experiment consisted of 4 blocks of 144 trials each. For half the subjects, the cue appeared in one of the HUD boxes for the first two blocks and on the runway for the final two blocks; for the remaining subjects, this order was reversed. Each block contained 36 replicates for the factorial combination of target location (HUD or runway) and target-nontarget relation (congruent or incongruent). Order of trial presentation was randomized separately for each subject and for each block.

<u>Procedure</u>. Subjects were tested individually in a sound-attenuated booth. They were told to imagine that they were piloting an airplane during final approach to a runway, and their task was to determine, as quickly and as accurately as they could, whether to proceed with the landing or initiate a go-around. They were then seated approximately 60 cm from the computer screen.

Each trial consisted of the following sequence of events. The HUD and the runway appeared for a preliminary period of 1.5 s, providing an opportunity for the subject to orient to the perceptual group in which the cue would occur. The cue was then presented, followed 250 ms later by the appearance of the geometric forms. The cue and geometric forms remained on the screen until the subject responded, or until the viewer appeared to pass over the runway stimuli on the way to touchdown.

Throughout the inter-trial-interval, subjects rested the index finger of their right hand on the center key of the numeric keyboard. They were informed that if the relevant target was a stop sign, the runway was closed, and they should signal their intention to do a go-around by striking the upper key as quickly as possible. Alternatively, if the relevant target was a diamond, the runway was open, and they should signal their intention to continue the landing by pressing the lower key as rapidly as possible.

## RESULTS

No upper limits were imposed on response times in the experiment. Most subjects yielded a few trials with very long response times (> 3 s), producing a large positive skew in the response time distributions. Data summaries and statistical analyses were therefore based on the median response time for each subject in each condition.

<u>Effects of trial type</u>. Figure 2 presents median response time averaged over subjects, as a function of cue location (HUD or runway) and relevant target location (HUD or runway). The figure shows that the effects

of relevant target location varied as a function of cue location; when the relevant target was on the HUD, subjects were 63 ms slower to respond when the cue was on the runway than when the cue was also on the HUD. Similarly, when the relevant target was on the runway, subjects were 148 ms slower to respond when the cue was on the HUD than when the cue was also on the runway. In a repeated measures ANOVA including cue location (HUD or runway), relevant target location (HUD or runway) and relevant target-nontarget relationship (congruent or incongruent) as factors, the two-way interaction of cue location (HUD or runway) and target location (HUD or runway) was highly significant, $F(1,19) = 42.2$, $p < .001$. The two-way interaction was also significant in an analysis of error rates, $F(1,19) = 9.0$, $p < .01$.

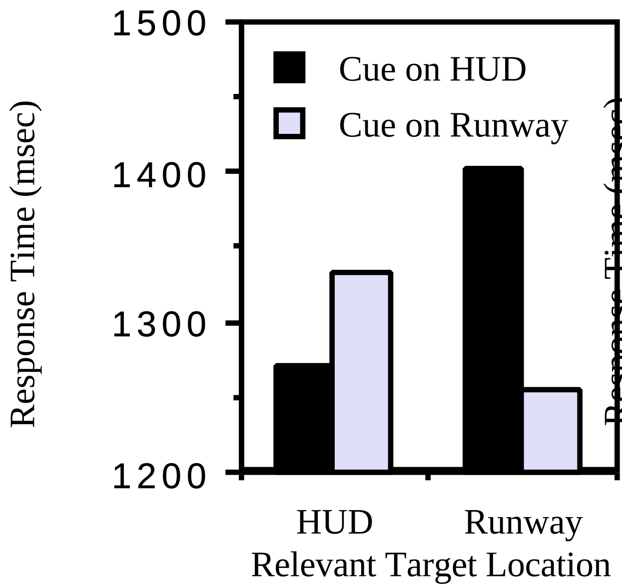


Figure 2. Interaction of Cue Location and Relevant Target Location

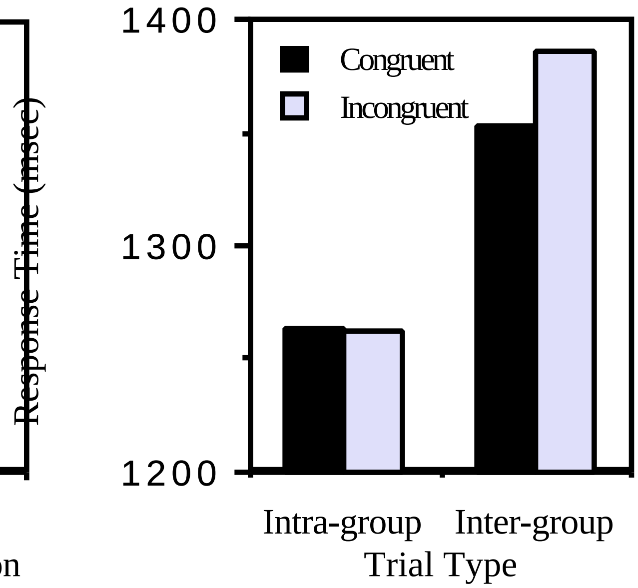


Figure 3. Interaction of Trial Type and Target-Nontarget Relation

<u>Congruency Effects</u>. Figure 3 plots the effect of relevant target-nontarget congruency separately for intra-group trials and inter-group trials. As shown in the figure, congruent cases were 33 ms faster than incongruent cases on inter-group trials, but virtually no congruency effect (-2 ms) was found on intra-group trials. Statistically, this pattern was reflected in a three way interaction between cue location, target location, and congruency, that was just short of significant, $F(1,19) = 4.24$, $p < .06$. Examination of error rates revealed a similar pattern: Congruency had only a small effect on intra-group trials (error rates of 2.9% for congruent cases vs 3.9% for incongruent cases), and a more substantial effect on inter-group trials (error rates of 3.1% vs 5.6%, respectively). The three way interaction of cue location, relevant target location, and congruency was significant, $F(1,19) = 5.98$, $p < .05$.

## DISCUSSION

Current models of visual information processing suggest that since HUDs are distinguished from the world by various perceptual cues, the visual system resolves the HUD as one perceptual group and the world as another. The present experiment tested two implications of this visual parsing: first, attentional limitations would prevent parallel processing of HUD-referenced information and world-referenced information, and second, transitioning from the HUD to the world (and vice versa) would involve a shift of attention. The results of the experiment supported both implications. When subjects focussed on the HUD for the duration of the trial, there was little effect of conflicting information in the world. Similarly, when subjects focussed on the world for the duration of the trial, there was little influence of conflicting information on the HUD. These results add to the findings of Fisher, et al. (1980) and Weintraub, et al. (1984) that when pilots focus attention on the HUD, objects in the world are excluded from processing.

The second hypothesis was supported by the fact that subjects were slower to respond on trials where they had to first process information from the HUD (World), and then process information from the world

(HUD), compared to trials were all relevant processing was confined to one group or the other. According to our data, the shift costs in transitioning from one group to the other are as much as 150 msec (for HUD-to-runway transitions).

It is important to note, moreover, that these values probably underestimate the magnitude of shift costs in the cockpit by a considerable margin. In our experiment subjects were not actively controlling the "descent", so their attentional focus may not have been as complete as that of pilots during an actual flight. Furthermore, our task formed a highly predictable situation: Subjects knew that a shift between perceptual groups was required on fully half of the trials; there was no temporal uncertainty concerning when shifting was to take place; and since the task involved a prescribed set of geometric objects, the nature of the stimuli to be processed was always known with certainty. In the real world, HUD-to-world (and world-to-HUD) transitions take place under much less predictable conditions.

Design implications. These results have clear implications for HUD design. Since HUDs do not seem to eliminate transition times between instrument processing and world processing, future HUDs should be developed with an eye toward removing the cues that cause the visual system to segregate HUDs from the world. For example, suppose that perspective cues and differential motion cues are in large part responsible for the segregation. The problem could be attenuated by designing HUD symbology to be as conformal as possible with the out-the-world scene. Further down the road, the development of synthetic visual displays offers an opportunity to incorporate HUD symbology into the world itself, as by placing forward airspeed information on virtual billboards (Foyle, et al., 1991). This approach would have the advantage of removing both perspective cues and motion cues.

## REFERENCES


Baylis, G. C., & Driver, J. (1992). Visual parsing and response competition: The effect of grouping factors. *Perception and Psychophysics*, *51*, 145-162.

Eriksen, B.A., & Eriksen, C. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception and Psychophysics*, 16, 143-149.

Fagot, C., & Pashler, H. Making two responses to a single object: Implications for the central attentional bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 1058-1079.

Fisher, E., Haines, R. F., & Price, T. A. *Cognitive issues in Head-Up Displays* (NASA Technical Paper 1711), Washington, D. C.

Foyle, D. C., Sanford, B., & McCann, R. S. (1991). Attentional issues in superimposed flight symbology. in R. J. Jensen (Ed.), *Proceedings of the Sixth International Symposium on Aviation Psychology*. Columbus: Ohio State Press.

Larish, I. A., & Wickens, C. D. (1991). *Divided attention with superimposed and separated imagery: Implications for head-up displays*. Unpublished manuscript.

Lauber, J. K., Bray, R. S., Harrison, R. L., Hemmingway, J. C., & Scott, B. C. (1982). *An operational evaluation of head-up displays for civil transport operations* (NASA Technical Paper 1815). Moffett Field, CA: NASA Ames Research Center.

Neisser, U., & Becklen, R. (1975). Selective looking: Attending to visually specified events. *Cognitive Psychology*, *7*, 480-494.

Treisman, A. M. (1982). Perceptual grouping and attention in visual search for features and for objects. *Journal of Experimental Psychology: Human Perception and Performance*, *8*, 194-214.

Weintraub, D. J., Haines, R. F., & Randle, R. J. (1984). The utility of head-up displays: Eye-focus vs. decision times. *Proceedings of the 28th Annual Meeting of the Human Factors Society* (pp. 529-533). Santa Monica, CA: Human Factors Society.

Yantis, S. & Johnston, J. C. (1990). On the locus of visual selection: Evidence from focussed attention tasks. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 135-149.