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MODELLING ATTENTIONAL EFFECTS WITH HEAD-UP DISPLAYS

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Previous research (McCann, Foyle, & Johnston, 1993) has shown that in a simulated approach to a runway, performance of a choice reaction time task is faster when all relevant information is available on the HUD or in the world, compared to when information has to be acquired from both domains. The present experiment tested two attentional models of these results: attention switching and attention sharing. Removing differential motion cues from the display, so that both the HUD and the world were motionless, attenuated the domain effect. The attenuated difference reflected both slower responses on within-domain trials and faster responses on between-domain trials. We conclude that performance with Head-Up Displays is affected by both attention switching and the ease of segregating domains.

INTRODUCTION

In a Head-up display (HUD) an image of the cockpit instruments is superimposed on the pilot's forward field of view. A large number of perceptual characteristics distinguish the HUD image from the outside world, including color, frame of reference, and differential motion. These cues are sufficiently salient that a HUD is frequently described as forming a near perceptual domain, and the outside world as a far perceptual domain (Wickens, Martin-Emerson, & Larish, 1993).

It is widely assumed that HUDs improve situational awareness compared to conventional head-down cockpits by allowing simultaneous processing of information in the two domains. However, studies of visual attention (e.g., Treisman, 1982; Duncan & Humphreys, 1989) suggest that when pilots are processing information in one domain (HUD or world), simultaneous processing of information in the other may be difficult or impossible.

McCann, Foyle and Johnston (1993) reported results consistent with this hypothesis. Subjects viewed a series of simulated approaches to a runway. Superimposed on the runway was a stationary HUD containing a series of pitch lines and four boxes. Following Weintraub, Haines & Randle (1984), subjects began each trial by monitoring either the HUD or the runway for a three-letter cue. If the cue spelled IFR, subjects searched for a target (stop sign or diamond) among a set of forms on the HUD. If the cue spelled VFR, they searched for the target among forms distributed across the surface of the runway.

This procedure yielded two kinds of trials. Within-domain (WITHIN) trials were those where all relevant stimuli (i.e. the cue and the relevant search set) were part of one domain or the other. An example would be when an IFR cue appeared on the HUD. The cue alerted the subject to search for the target among the geometric forms on the HUD; no processing of stimuli in the world was logically required. Between-domain (BETWEEN) trials were those where the cue was part of one domain, and the relevant search set was part of the other. An example of a BETWEEN trial is when a VFR cue appears on the HUD; the correct procedure is to locate and respond to the target on the surface of the runway.

The results of the experiment were straightforward. Response times were considerably faster on WITHIN trials than on BETWEEN trials, both when the cue appeared on the HUD (in which case the slower BETWEEN trials reflected a shift from processing HUD information to processing world information) and when the cue appeared on the runway (in which case the slower BETWEEN trials reflected a shift from processing world information to processing HUD information). The interaction of cue domain (HUD or runway) with target domain (HUD or runway) was highly significant. We refer to this interaction as a WITHIN-BETWEEN effect.

MODELS OF WITHIN-BETWEEN EFFECTS

The goal of the present experiment was to distinguish between two models of WITHIN-BETWEEN effects. Both models assume that attention is focussed on the cue domain during the initial phases of a trial, and that attention is also required in the final target search phase. The models differ critically in how attention is assumed to be distributed during the target search phase in the BETWEEN condition. The *switching* model assumes that subjects stop attending to the cue domain, focussing attention exclusively on the target domain. The *sharing* model assumes that attention is divided between the domains.

Both models predict that BETWEEN conditions will be more difficult than WITHIN conditions, but for different reasons. According to the switching model, the BETWEEN condition target search phase is delayed due to the time required to switch attention from the cue domain to the target domain (Treisman, 1982). According to the sharing model, it proceed more slowly because attention is spread across two domains rather than one (Duncan & Humphreys, 1989).

THE PRESENT EXPERIMENT

The present experiment was designed to distinguish between the two models. The logic is as follows. Since both accounts assume that WITHIN-BETWEEN effects are a consequence of having segregated the visual scene into a near domain (the HUD) and a far domain (the world), WITHIN-BETWEEN effects ought to be reduced if some of the perceptual cues that distinguish the domains are removed. In the McCann et al. (1993) procedure, three cues were identified as particularly salient domain distinguishers: color, motion, and frame of reference. Available evidence suggests that color and motion are particularly effective cues for segregation (Baylis & Driver, 1992; McLeod, Driver, Dienes, & Crisp, 1991).

The present experiment attempted to modulate WITHIN-BETWEEN effects by manipulating the availability of the color and motion cues. On some trials the HUD was drawn in light blue and the world in light yellow; on others both the HUD and world were drawn in light yellow. On some trials, world stimuli moved, simulating final approach; on other trials the world was "frozen" during the trial.

When the perceptual cues that support domain segregation are removed, WITHIN-BETWEEN effects should be reduced. The attention-switching model and the attention-sharing model posit different mechanisms for the reduction. According to the former, a reduction in the size of the effect would mean that attention switching was taking less time (or perhaps was being bypassed completely); therefore, BETWEEN trials should get faster. No change on WITHIN trials is hypothesized. If, however, WITHIN-BETWEEN effects are due to attention sharing, removing perceptual cues should produce more attention sharing between the domains on WITHIN trials. Processing on WITHIN trials should therefore proceed less efficiently. The sharing model thus predicts that reductions in the magnitude of the WITHIN-BETWEEN effect should reflect a slowdown on WITHIN trials; no effect on BETWEEN trials is hypothesized. These predictions are opposite to those of the switching model.

METHOD

Subjects

The subjects were 48 students at San Jose State University. All were between the ages of 18 and 40, and reported normal or corrected-to-normal vision. For half of the subjects, the IFR/VFR cue always appeared in one of the lower boxes on the HUD. For the remaining subjects, the cue always appeared on the surface of the runway.

Stimuli and Apparatus

The experiment was conducted on an IBM-compatible personal computer equipped with an Intel 486 microprocessor. All phases of the experiment were controlled by the computer.

Stimuli were presented on a CRT screen. The "world" domain consisted of a horizon line extending across the screen (14 cm from the bottom) and below it a perspective-view runway consisting of a trapezoidal outline 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. The HUD domain consisted of a superimposed stationary series of pitch lines, four small boxes, (two on the left and two on the right), and an airplane symbol. The boxes measured 1.9 cm in width and 1.1 cm in height, with a vertical separation of .6 cm and a left-right separation of 5.4 cm. When the color cue was present, the HUD was drawn in light blue and the world in light yellow. When the color cue was absent, both domains were drawn in light yellow.

The experimental stimuli consisted of two three-letter cues (IFR or VFR), a target (stop sign or diamond) and two distractor stimuli (triangle and square). Each display contained a target and two distractors in the relevant domain, and a "pseudo-target" and two distractors in the irrelevant domain. The target and pseudotarget could be either congruent (both stop signs or both diamonds) or incongruent (one a stop sign, the other a diamond). The HUD symbols occupied 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 symbols appeared in analogous locations directly below the HUD. When the cue appeared on the runway, it occupied the fourth analogous location, either the top right or the top left. Consistent with the constraints imposed by the dynamic nature of the runway stimuli in some conditions (see below), 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 equated.

Motion

When the motion cue was present, the subject appeared to be on final approach to a runway (displayed at a 12 hz update rate). Small random vertical and lateral perturbations simulated pitch and yaw buffeting. Trials began approximately 5 sec before touchdown, considerably longer than required to do the task. In the motion-cue absent condition, the world was frozen with a view corresponding to approximately 4 sec prior to touchdown.

Design and Procedure

Subjects were run individually in a sound-attenuating booth. Each subject was instructed to imagine that they were landing a plane, and that each trial represented a new approach. Their task was to communicate their intention to either complete the landing or initiate a go-around. At the beginning of each trial, subjects rested their right index finger lightly on the "5" key located in the middle of the numeric keyboard. They used this finger to press the "8" key for diamond targets (continue the landing) and the "2" key for stop sign targets (go around). All subjects were instructed to respond as rapidly as possible without making too many errors.

The experiment consisted of 4 blocks of 144 trials each. Each block contained 36 replicates for the factorial combination of target domain (HUD or world) and target-pseudotarget relation (congruent or incongruent). Perceptual conditions were blocked according to the four combinations of color cue (present or absent) and motion cue (present or absent). The order of trial presentation was randomized separately for each subject and each block.

RESULTS

Response times

No upper limits were imposed on recorded response times in this experiment. To avoid serious outlier problems, median response times were the chief dependent variable analyzed. A preliminary analysis of variance (ANOVA) was carried out on the between-subjects factor of cue domain (HUD or World) and four within-subject variables: target domain (HUD or world), target-pseudotarget congruence, color (present or absent), and motion (present or absent). With the exception of one four-way interaction that we did not try to interpret, no effects involving either color or congruence reached significance.

Accordingly, a second ANOVA was performed including only motion, cue domain, and target domain as factors (see Figure 1). Subjects were faster overall when the target was on the HUD than when it was in the world, $F(1,46) = 4.51$, $p < .05$. When the cue was on the HUD, subjects responded faster when the target was on the HUD than when the target was on the runway; this pattern was reversed when the cue appeared on the runway. The crossover interaction of cue domain by target domain (i.e., the BETWEEN-WITHIN effect) was highly significant, $F(1,46) = 28.45$, $p < .001$, replicating McCann, et al. (1993).

Most important for present purposes, there was a significant three-way interaction of cue domain, target domain, and motion, $F(1, 46) = 13.23$, $p < .001$. The three-way interaction is illustrated in Figure 1. With motion cues, (upper panel), the crossover interaction between cue domain and target domain was striking; however, when the world was frozen (lower panel) the magnitude of that interaction was reduced considerably. Domain effects were attenuated when differential motion was no longer available to facilitate domain segregation.

The critical question is how the reduction in the size of the BETWEEN-WITHIN effect (i.e., the crossover interaction) was achieved. Comparing corresponding points in the upper and lower panels, we see that removing motion cues was associated with *both* a slowing of WITHIN trials and a speedup of BETWEEN trials.

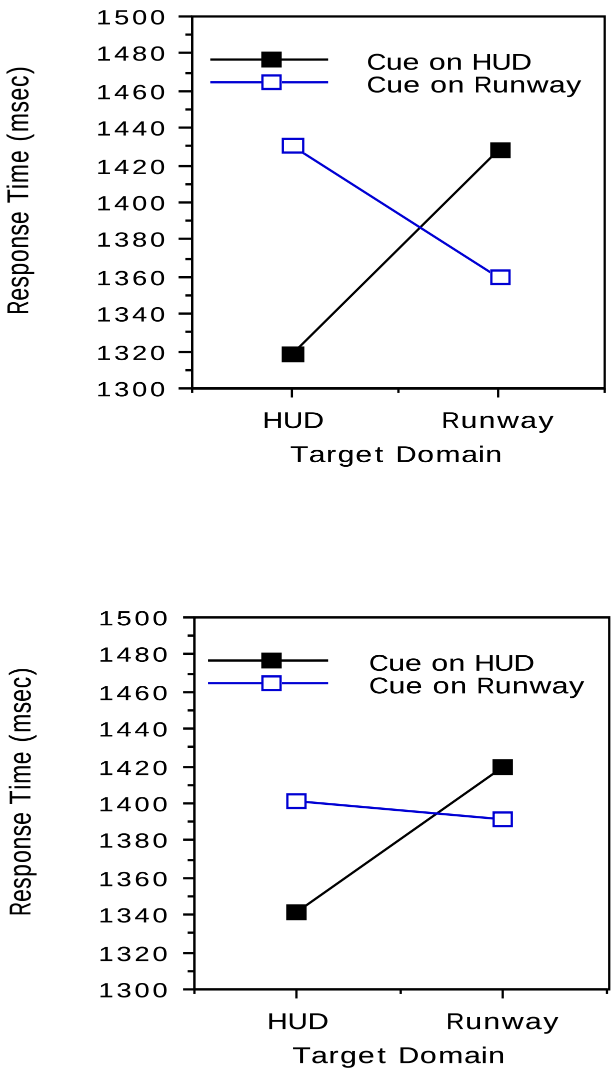

Figure 1. Upper panel illustrates the interaction of cue and target domain with motion cues; lower panel illustrates the same interaction without motion cues.

An additional aspect of the three-way interaction is worth noting. When the IFR/VFR cue was on the HUD, removing motion cues reduced the advantage of WITHIN trials over BETWEEN trials by only a modest amount (110 ms to 76 msec). When the IFR/VFR cue was part of the world, removing motion cues reduced the advantage of WITHIN trials over BETWEEN trials from 70 ms to only 10 ms. Separate analyses revealed that the interaction between motion and target domain was significant among subjects presented with the cue on the runway, $F(1, 23) = 22.19$, $p < .01$, but not among subjects presented with the cue on the HUD, $F(1, 23) = 2.26$, $p > .10$.

<u>Error analysis</u>

Results of an analysis of error rates generally mirrored the results of the response time analyses; most importantly, the cue domain by target domain interaction was significant, $F(1, 46) = 10.31$, $p < .005$, reflecting generally higher error rates for BETWEEN trials than WITHIN trials. In addition, however, error rates were 3.68% when the target and pseudotarget were congruent, compared to 6.2% when they were incongruent $(1,46) = 40.37$, $p < .001$; this effect was not present in the analysis of response times. Furthermore, the two-way interaction between congruence and target domain was significant, $F(1,46) = 4.66$, $p < .05$, as was the three-way interaction between congruence, target domain, and cue domain, $F(1,46) = 4.48$, $p < .05$. The three-way interaction results from unusually small effects of congruence (1%) on WITHIN trials in the HUD domain.

GENERAL DISCUSSION

The present experiment replicated McCann et al.'s (1993) finding that BETWEEN trials are slower than WITHIN trials. The present study provides further support for the hypothesis that attentional constraints reduce a pilot's ability to process HUD information and world information simultaneously. The experiment also produced a number of new findings. First, the performance penalty for BETWEEN vs. WITHIN trials was reduced when the domains were made less discriminable (i.e. by removing motion cues). Second, the reduction reflected both an increase in response times on WITHIN trials and a decrease on BETWEEN trials. This suggests that the penalty for BETWEEN domain performance is a product of both attention shifting and interference from the irrelevant domain. Third, the removal of motion cues reduced the BETWEEN domain penalty asymmetrically: when the cue appeared on the HUD, the BETWEEN penalty was reduced by only a modest (nonsignificant) amount. In contrast, when the cue appeared on the surface of the runway, the BETWEEN penalty was virtually abolished. Fourth, congruence effects were also asymmetric; when processing was confined to the HUD, there was little effect of an incongruent pseudotarget on the runway; an incongruent pseudotarget on the HUD, however, reduced accuracy to runway targets even when processing was logically confined to the runway.

These findings have a number of practical implications. First, segregation of the near (HUD) domain and the far (world) domain can be either a help or a hindrance to human performance, depending on the processing requirements of the task at hand. When the task requires the pilot to focus exclusively on information in one domain or the other, maximizing perceptual segregation is optimal. On the other hand, when the task involves acquiring or monitoring information in both near and far domains, segregation introduces attention switching costs, and can be detrimental. Segregation may be particularly harmful when the pilot must abruptly transition from processing the near domain to the far domain, as when the outside world is first "acquired" during low visibility landings. These HUD principles mirror the proximity compatibility principles developed by Wickens and his colleagues in other contexts (e.g., Wickens & Andre, 1990).

Two processing asymmetries merit further discussion. The first asymmetry is that congruence effects were stronger on WITHIN trials involving world processing than on WITHIN trials involving HUD processing. This result suggests that subjects were less successful at "gating out" information on the HUD when attention was supposed to be focussed on the world than vice versa. The second asymmetry is that removing motion cues abolished the advantage for WITHIN vs. BETWEEN trials among subjects beginning with world cues, but failed to significantly reduce that advantage among subjects beginning with HUD cues. This result suggests that the ability to restrict attention to the HUD is more robust than the ability to restrict attention to the world.

Both asymmetries follow quite naturally from one simple postulate: that the HUD acts as an attentional "trap" or attentional "attractor", so people are less able to focus attention exclusively on the runway (and ignore the HUD) than vice versa. One important implication of this idea is that the presence of a HUD may interfere substantially with processing information in the world, even when no actual obscuration of world-referenced information is occurring.

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