THE INFLUENCE OF BRIGHTNESS CUEING ON EYE MOVEMENTS WITHIN A COCKPIT DISPLAY OF TRAFFIC INFORMATION

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Several experiments were conducted to examine the effect of brightness highlighting on search of a target aircraft among distractor aircraft within a cockpit display of traffic information (CDTI). The present experiment partially replicated the design of one of these experiments, adding an examination of eye movements. The display presented homogenous all bright, all dim, or mixed bright and dim aircraft. Within the mixed display, target aircraft were non-predictive and either bright or dim. Results showed that with the mixed display, participants yielded slower detection times, exhibited more eye fixations, and searched with longer paths, compared to the homogenous all bright or dim displays. The duration of the fixation and the speed of eye movements did not show any difference between the homogeneous and mixed displays. The present detection time analysis did not replicate previous experimental results and this is likely due to the fewer trials given in the current experiment. The present results demonstrated how using highlighting to segregate information domains may impose costs on visual search performance in the early stages of a search task.

INTRODUCTION

Enhancing visual search performance is important in designing a Cockpit Display of Traffic Information (CDTI). A CDTI must depict sufficient information to provide pilots with situation awareness, while keeping attentional demands and time-to-search at a minimum. There are several possible approaches to achieve this goal. One is to use visual features such as highlighting to segregate information on a display into more and less important items, and using these features to direct attention. For example, Wickens, Ambinder, Alexander, and Martens (2004) segregated two information domains on a cluttered map display by varying intensity level of one domain. It was found that by lowlighting one information domain and keeping the other at a fairly high intensity level, performance on vehicle dispatching tasks (which required both focused and divided attention) could be optimized. On the other hand, how highlighting can direct a user's initial attention to targets and therefore reduce search time has also been studied (e.g., Smith & Goodwin, 1971, 1972; Stewart, 1976). However, the benefits of such highlighting appear to be contingent on either bottom-up factors, such as the type of highlighting (e.g., color, brightness, blinking), or top-down factors, such as the level of highlighting validity, and the probability that operators attend to the highlighted options first (Fisher & Tan, 1989).

A number of experiments have been conducted to investigate the effects of brightness highlighting on visual search performance within a CDTI (Johnson, Liao, & Tse, 1999; Johnson, Liao, & Granada, 2002; Johnson, Jordan, Liao, & Granada, 2003). The present experiment followed on one of these experiments to further investigate the highlighting effect within a CDTI. In Johnson et al.'s experiments (2002, 2003), the task was to search among several aircraft for a target aircraft on a collision course with Ownship. Brightness levels of the target and the distractor aircraft were manipulated. In those experiments, the simultaneous impact of both top-down and bottom-up control of attention during visual search was investigated. In Johnson et al.'s experiment (2002), three display conditions were presented: displays with homogeneous all bright aircraft, all dim aircraft, and mixed bright and dim aircraft. In the mixed display, the target aircraft could be bright or dim. A pure bottom-up effect was examined where target brightness was non-predictive (zero validity). That is, participants had no clue whether the target aircraft was bright or dim on the mixed display. On the other hand, a top-down effect was also examined where participants were informed whether the target was bright or dim on the mixed display (full validity). An interesting finding was that within the zero validity condition, detection of the bright targets on the mixed display was no faster than detection of dim or bright targets on the homogenous displays. Instead, detection of the dim targets on the mixed display slowed down. These results were similar to those found by Kroft and Wickens (2001), who reported that processing of information from lowlighted parts of a display was negatively impacted, while processing of highlighted information was not affected for good or ill.

Regarding Johnson et al.'s finding (2002), if the dim targets were looked at but not recognized as targets, overall search times would have been extended until the dim targets were re-sampled and perceived correctly. This could be explained as a pure perceptual effect. Alternatively, a decision bias may have led participants to reject bright or dim distractor aircraft at the same rate, but take longer to confirm a dim target. In either case, bright targets on the mixed display would be detected equally fast as on the homogenous displays, while detection of dim targets would be delayed on the mixed display. Johnson et al. (2003) further investigated these two hypotheses using signal detection theory methodology. A speeded search task was used that allowed only a brief amount of time to detect the target. The results paralleled those from Johnson et al. (2002). That is, only the accuracy for dim target detection decreased on the mixed display when there was zero validity. Furthermore, it appeared that degraded dim target detection performance was solely due to differential sensitivity, not differential decision criteria.

The present experiment replicated the zero validity condition of Johnson et al.'s experiment (2002) with an additional examination of eye movements. Eye tracker systems have emerged as a new technology to study human information processing or cognitive processes over the past two decades (see Rayner, 1998 for review).

In summary, Johnson et al.'s experiments (2002, 2003) with measures of detection time and response accuracy showed that using brightness highlighting to segregate a CDTI into two information domains but with no validity of target brightness could negatively impact the detection of a dim target. Furthermore, impacts to perceptual processes, rather than to decision-making process, appeared to be responsible for these results. The present experiment further investigated this highlighting effect by examining the eye movements during search. It was hoped that by examining eye movement characteristics such as how many fixations the operator exhibited, how long the fixations lasted, and how fast the eyes were moving on the display, we would gain more insight into the effect of brightness highlighting on visual search performance on a CDTI.

METHOD

Participants' task was to detect a target aircraft amongst eight alternatives on a collision course with Ownship within a CDTI. Display (Homogeneous – either all bright or dim alternatives vs. Mixed – mixed bright and dim alternatives) and Target Brightness (target was bright vs. dim) were two within-participants variables. Participants' eye movements were recorded during their search. Detection time, number of eye fixations, duration of eye fixation, and eye movement path length and movement speed were measured. Additionally, aircraft closest to a fixation were considered "fixated aircraft" if they were within a range of 2.2 degrees of visual angle around that fixation. It was hoped that by examining brightness levels of the fixated aircraft, participants' search strategies, particularly with mixed bright and dim alternatives on the display, could be revealed.

Stimuli and Design

The experiment utilized a CDTI (25 degrees of visual angle square) with one Ownship symbol depicted by a white filled triangle (chevron) located at the bottom of the display, and eight other aircraft symbols (unfilled chevrons) pseudo-randomly placed throughout the rest of the display (Figure 1). Chevron orientation corresponded to the direction the aircraft were traveling. The CDTI was partitioned into four equally sized x-y regions with two aircraft randomly located in each region, generating a total of eight aircraft on the display. The target appeared equally often in each region to minimize possible location effects. The placement and heading of each non-target aircraft was designed to miss Ownship by a visually wide margin. All the aircraft were stationary on the display and their altitudes and speeds were the same. It was thus obvious when an aircraft was a target. The luminosity (intensity) levels for bright and dim aircraft were 1.81 cd/m^2 and 0.28 cd/m^2, respectively, against a black background of 0.0014 cd/m^2.

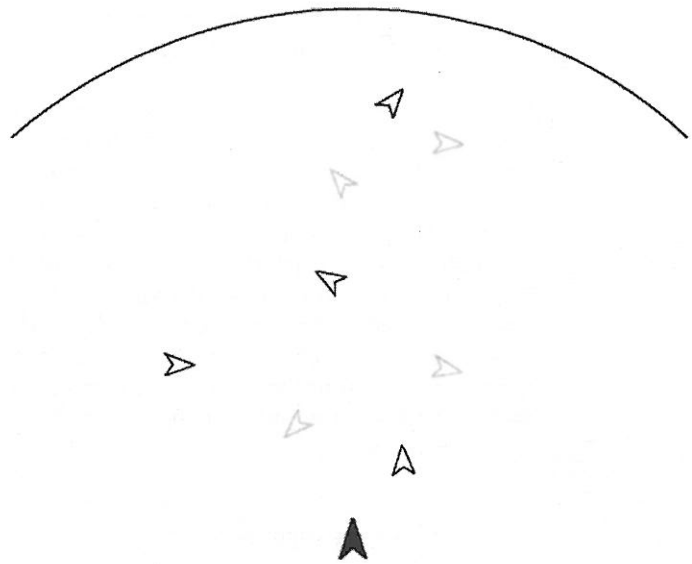

Figure 1. CDTI used in the experiment. Colors inverted for better-printed depiction.

Participants

Twelve participants (6 females, 6 males) volunteered their time to participate in the experiments. Each participant had normal or corrected-to-normal vision.

Apparatus

A Pentium IV system with a 17-inch diagonal LCD (1024 x 1280) display was used. Viewing distance was approximately 24 inches, and the display update rate was 60 Hz. Eye movements can be monitored in many different ways. The ISCAN eye tracker system used in the present experiment monitored the position of the pupil and corneal reflection landmarks in an eye image in real time. It used non-invasive video-based dark-pupil-to-corneal reflection method to monitor the position of the participant's eye and measure the pupil size in real time.

Procedure

The experimenter explained the main aspects of the task and procedures to each participant and then participants received eight practice trials. Participants were not informed whether the target would be bright or dim on the Mixed display. They were simply told to detect the target aircraft regardless of the brightness of the aircraft. Participants then put on a light headband with an eye tracker attached, which they wore throughout the rest of the experiment. The experimenter calibrated the eye tracker for each participant before proceeding to the experiment. For each trial, participants were to detect the one (target) aircraft on a collision course with Ownship. Once the target was detected, participants pressed a button on a mouse indicating the target had been found. Measured detection time thus was the elapsed duration between the onset of the aircraft on the display, and the time when the mouse button was pressed. After the button was pressed, non-directional circles replaced the aircraft symbols, and the participants were instructed to use a mouse cursor to select the circle where the target aircraft was previously located. This procedure assured that detection time was measured independent of the time needed to move the mouse to the target, and also served to verify that participants had found the correct aircraft.

Each participant received three blocks of trials, one for each display condition. There were 16 trials on the two Homogenous displays and 32 trials on the Mixed display. Of the 32 trials on the Mixed display, half of them had a bright target and half of them had a dim target. Trials with bright and dim targets were randomly presented to participants within the block. Each participant completed a total of 64 trials. The order of presenting the Homogenous and Mixed displays was counterbalanced across participants. Participants' eye positions during the search were sampled at 60 Hz rate by the computer.

RESULTS

Time to detect the target in each trial was measured. For the eye movement data, the current experiment first defined a fixation as having occurred when the measured eye position remained approximately stable for more than 150 ms. A fixated aircraft was determined by finding the aircraft closest to the fixation, and then defining it as fixated if it was within 2.2 visual degrees of the fixation point. For each trial, all fixations were first identified, then their durations were measured and the total number of fixations within the trial were calculated, as well as the average eye movement path length and movement speed during search. Furthermore, the percentage of fixations with bright-fixated aircraft within each trial was also calculated.

Repeated measures analyses of variance (ANOVA) were performed for each of the dependent measures: *detection time, number of eye fixations, eye fixation duration, and eye movement path length and speed.* The independent variables were *Display* (Homogeneous vs. Mixed display) and *Target Brightness* (Bright Target vs. Dim Target). Additionally, a two-tailed t-test was conducted for the Mixed display condition. The percentage of fixations with bright-fixated aircraft within each trial was a dependent variable. The purpose of performing this t-test was to test for bias toward examining bright or dim aircraft more often during search, which would show in a higher or lower percentage of bright-aircraft fixations.

For each participant, trials with the incorrect response, or with the detection times beyond three standard deviations from the average detection time, were dismissed from the analyses. Overall, about 7.6% of trials were dismissed.

Detection time. The analysis of detection time showed a significant main effect of Display ($F(1,11)=16.27$, $p=0.002$). The detection times were significantly slower in the Mixed display condition compared to the Homogenous display condition (M=3.55 vs. 3.13 sec) (Figure 2). There was not a significant interaction between Display and Target Brightness. Note that in Johnson et al.'s experiment (2002), a significant interaction was found which showed that the mean detection time for dim targets on the mixed display was higher than that for bright targets on the mixed display and higher than the detection times on either homogeneous display. The present finding did not replicate this previous result.

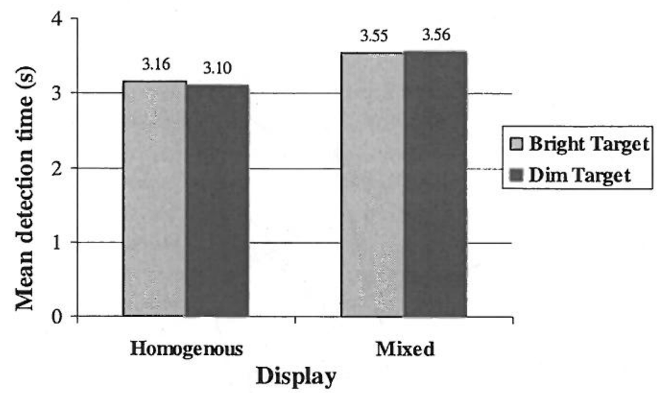

Figure 2. Detection time as a function of Display and Target Brightness.

Number of eye fixations and fixation duration. The analysis of the number of fixations yielded main effects of Display ($F(1,11)=5.318$, $p=0.042$) and Target Brightness ($F(1,11)=5.563$, $p=0.038$) (Figure 3). Although there appears to be an interaction between Display and Target Brightness, with more fixations when the target was dim in the mixed display condition, this was not statistically significant ($p = 0.134$). Figure 3 shows there were more fixations when searching on the Mixed display than on the Homogeneous display (M=4.06 vs. 3.54). Furthermore, there were more fixations when the target was dim than when the target was bright (M=4.06 vs. 3.54). The fixation duration analyses did not yield any significant effects.

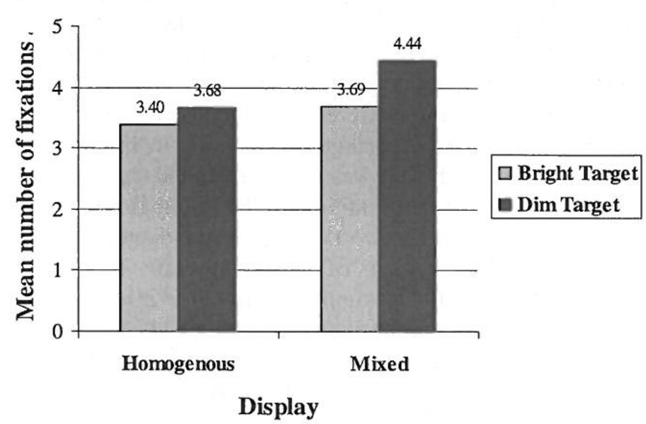

Figure 3. Fixations as a function of Display and Target Brightness,

Eye movement path length and speed. Example of eye movement paths in one trial (Mixed, Dim Target condition) from one participant is presented in Figure 4 where Ownship is at the center bottom of the display (black triangle) while the dark gray triangles represent dim aircraft and light gray triangles represent bright aircraft. The arrows along the movement trajectory show the movement speed, with arrow length proportional to eye movement speed. Finally, the little circle indicates the initial eye position.

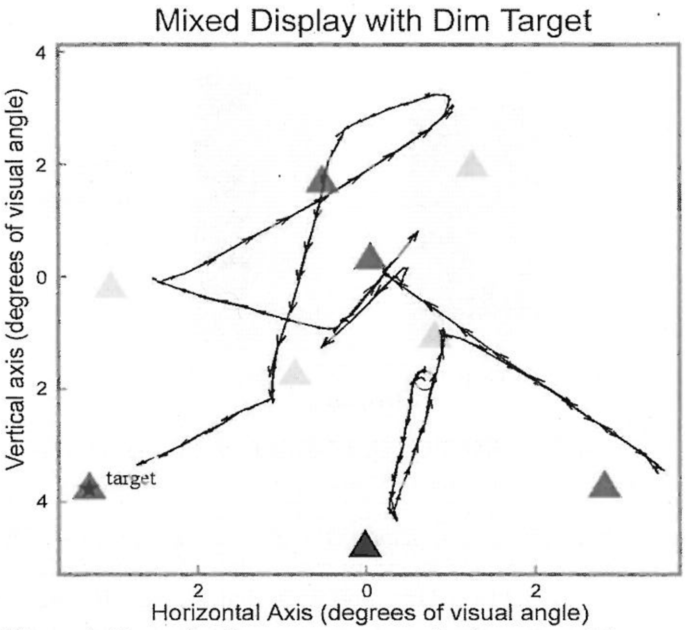

Figure 4. Example of eye movement paths from one trial.

The result of the eye movement path length analysis paralleled that for the detection time analysis. The mean movement path length was significantly longer for the Mixed display than the Homogenous display (M=45.79 vs. 41.21 degrees of visual angle, $F(1,11)=11.79$, $p=.006$). The analysis for the eye movement speed did not exhibit any significant effects.

Fixations for bright aircraft vs dim aircraft. With the Mixed display, if participants had no bias to attend more frequently to bright (or to dim) aircraft, then on average there should be approximately equal fixations for the two (i.e., about 50% of fixations were for bright aircraft and 50% for dim aircraft). The percentage of fixations to bright and dim aircraft within each trial was therefore calculated. There were on average 55% of the fixations for the bright aircraft and 45% for the dim aircraft. A two-tailed t-test conducted to examine whether the percentage of bright aircraft fixations was deviated from 50% was significant ($t(11) = 2.198$, $p = 0.05$). This effect was similar across Dim and Bright Target conditions and demonstrated that participants checked more bright aircraft than dim aircraft on the Mixed display.

In summary, in this experiment the main effect of Display on detection time, number of eye fixations, and eye movement path length were all consistent with a mixed bright/dim display delaying target detection by increasing the number of fixations and movements. In addition, analyses of fixation duration and eye movement speed revealed that this delay did not result from either the longer fixation duration or from slower eye movements. However, the present detection time result did not replicate the previous experimental result (Johnson et al., 2002), which showed only dim targets in the mixed condition being delayed. Finally, there was a greater number of fixations of bright aircraft than of dim aircraft on the Mixed display. This suggested that participants had checked more bright aircraft before they finally detected the target.

DISCUSSION

An informal examination of the eye-movement data suggested that, due to a small display size, it may not be necessary for participants to precisely fixate each individual aircraft during a search. Rather, they could simply fixate one spot and used their peripheral vision to check several aircraft at the same time. Also, periodic tests often showed a slight deviation between an instructed fixation location, and the fixation point measured by the eye tracking measurement system. The present analysis therefore searched within a range of about two degrees of visual angle around a fixation to identify the closest aircraft and assumed that it was the aircraft that was fixated. It was hoped that by doing so the effects of brightness highlighting on participants' search strategies could be more clearly revealed.

A major issue in the present experiment was that we did not fully replicate results from the previous experiment (Johnson et al., 2002). Specifically, detection times for dim and bright targets in the mixed display condition were equivalently prolonged; while in the previous study only the dim targets in the mixed display condition was prolonged. One possible reason was the different number of trials given. In the previous experiment, participants received more than 400 trials and the analyses were based on the average of all the trials. In the current experiment, however, due to a concern that a long experiment may cause discomfort in wearing the eye tracker system, only 64 trials were presented. We therefore re-analyzed Johnson et al.'s (2002) data including only the first 16 trials from each display condition. The analysis showed a significant main effect of Display ($F(1,23)=7.26$, $p=.013$), where the average detection times for the Mixed displays was greater than that for the Homogeneous Displays (M=1.76 vs. 1.58 sec). Figure 5 shows the average detection times for the first 16 trials of each display condition and for all the trials from Johnson et al.'s experiment (2002), as well as for all the 64 trials from the current experiment, as a function of Display and Target Brightness. Overall, the data from the early practice (first 16 trials) of Johnson et al.'s experiment (2002) seems to resemble the current data, that is, an equivalent delay in detection times for the dim and bright targets in the mixed display condition. Practice then seems to play a role in the current visual search task. Note, however, that the current average detection times were much greater than that of Johnson et al.'s experiment (2002). It was likely that wearing the eye tracker made participants feel awkward in moving their heads and hands and so their responses were slowed down.

McCarley, Kramer, Wickens, Vidoni, and Boot (2004) examined the effect of practice on performance of visual scanning and target detection-recognition in a simulated airport-security inspection task. Participants in their experiment went through several sessions and overall received 300 trials of practice. It was found that both sensitivity and reaction time significantly improved with practice. Their study thus provided evidence for the effect of practice on visual search and target detection performance.

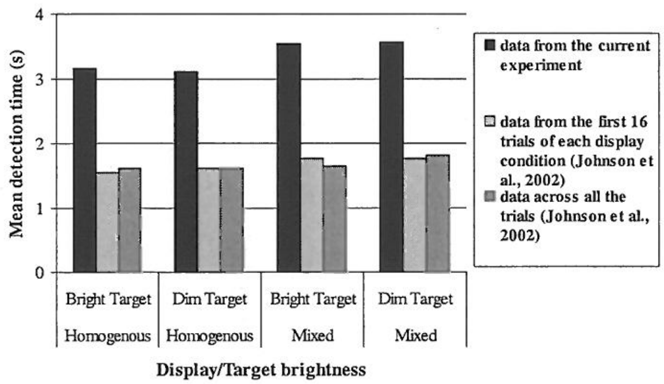

Figure 5. Detection times from Johnson et al.'s (2002) and the current experiments.

On the other hand, Wickens et al. (2004) summarized two competing predictions for performance of tasks that require divided attention between one highlighted and one lowlighted domain on the display. One prediction was that, although segregating items into two groups will cause additional integration effort, the reduced clutter on the display will eventually compensate for the cost of integration and result in greater benefits. Also, the salience benefit for the highlighted group is assumed to offset the low-salience cost of the lowlighted group. In the current experiment with a Mixed display, it was probable that, for the early trials, the cost of searching across mixed highlighted (bright) and lowlighted (dim) domains overshadowed any potential benefits. Therefore, participants' overall performance with the Mixed display was degraded compared to performance using the Homogenous displays. However, with practice, the benefits of reduced clutter, and of salient (bright) aircraft eventually overcame this drawback, and participants' performance in the detection of bright targets, in particular, improved. Unfortunately the present experiment only examined participants' eye movements at the early stage of practice. A follow-up experiment is currently planned where participants will receive the same number of trials as in Johnson et al.'s experiment (2002), and the eye tracker system will not be implemented until the last 64 trials. It is hoped that the new experiment will provide some insights into this potential highlighting and practice interactive effect.

Finally, the task adopted here was different from typical visual search experiments where simple and straightforward responses are generally required. The present target search task required more cognitive processes given that participants needed to examine the heading of each aircraft and decide which aircraft was on a collision course with Ownship. How the effect of highlighting interacts with this task complexity needs further research. Simple modifications such as changing the chevron symbol to circle and defining the target based on a different feature could address this issue.

In conclusion, the present experiment suggested that segregating information into two highlighting domains with zero highlighting validity, hindered target detection performance, at least in the early stage of practice. The current detection time, eye fixation, and eye movement path length analyses all revealed this effect. On the other hand, fixation duration and the eye movement speed were not affected by the segregation of information domains. This supports the idea that search on the Mixed display was delayed mostly due to re-examination or re-sampling process, not the additional time spent on each aircraft per se. This would also agree with the conclusions from the previous experiments (Johnson et al., 2002, 2003) that the perceptual process plays a more important role in visual search on a CDTI than the decision-making process. Therefore, the impact of mixing bright and dim aircraft to segregate information domains on the CDTI primarily influenced participants' search patterns, not how fast they moved and how long they fixated each aircraft.

The implication of the present results for display design is that using highlighting to segregate information domains with zero highlighting validity may harm visual search performance in the beginning of practice. However, with sufficient practice, placing targets among physically more salient (brighter) alternatives may eventually benefit performance.

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