

INTEGRATING AVIATION DATABASES: EFFECTS OF SCANNING, CLUTTER, RESOLUTION,  
AND INTERACTIVITY

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ABSTRACT

The overlay of multiple databases enables electronic map designers to present pilots with more information within the same amount of space. This technique may also have the advantages of increased display resolution and reduced scanning. One potential drawback, however, is the presence of additional clutter. In addition, interactive decluttering techniques will increase information access cost. The present experiment sought to quantify the effects of both the benefits and drawbacks of display integration. Pilots used six different, high-clutter digitized displays containing navigation information and air hazard information to answer attention questions. Responses were faster when the databases were integrated than separated, particularly when questions required integration across both of the databases, where accuracy also was greater. These results suggest that the combined benefits of reduced scanning and higher resolution outweigh the costs of clutter. Interaction of any sort imposed a time cost (with no accuracy benefit) which was greatest when the questions involved both databases.

INTRODUCTION

Increases in the computational power and memory of modern computers make it possible for designers to present more information to aircraft pilots. At the same time, however, the area where information can be displayed, the display "real estate," is a relatively fixed parameter. One possible solution to this problem is to display multiple sources of data in one overlaid display. Integrating multiple displays into one single display would allow designers to present more information, while at the same time conserving display space.

Domain or database integration through overlay, however, is not a clear-cut solution to the problem. While the implementation of integration can have positive effects, it can also potentially cause performance detriments (Wickens, 2000).

When databases are overlaid, as opposed to being presented them separately, pilots no longer have to make eye or head movements from one display to the other. In addition, since the domains already exist in the same spatial area, the pilot no longer has to mentally integrate the information in the displays. On the other hand, the clutter of the display, both the number of objects within the display and the density of information around a given point, increase. In conjunction, this trade-off is known as the clutter-scan trade-off and has been investigated by numerous experiments (see Fadden et al, 1998, 2000; Hofer, Palen, and Possolo, 1993; O'Brien and Wickens, 1997; Srinivasan and Jovanis, 1997; Ververs and Wickens, 1998; Wickens and Helleberg, 1999; and Wickens and Long, 1995). The results from the studies show, that the benefits of scanning reduction generally outweigh the costs of increased clutter. Despite this outcome, however, the results of increased clutter can still be observed in the user's performance, and are amplified when attention must be focused only on one of the databases.

Another benefit of database overlay is the potential to increase the resolution of the display. When several displays are combined into one display, the resulting single display can be made larger when positioned in the area previously occupied by the multiple displays. Larger displays can present information, especially text and symbols, at a greater size, making them easier to read.

The cost of increased clutter may be offset through the use of decluttering techniques that lowlight or remove portions of the display and allow user to focus on the highlighted information. While several different implementations are available, we chose to examine three different types, fixed lowlighting, interactive lowlighting, and interactive decluttering. Lowlighting displays present one domain of information at a brighter luminance level than the other aspects of the display, while the decluttering display removes a domain entirely. Interactive displays allow the user to manipulate which domain is highlighted, and

fixed displays cannot be changed. Although the increased flexibility of interactive displays may appeal to some users, the added cost of interaction with the system may cause performance detriments to response times or accuracy. Despite this potential drawback, research investigating both lowlighting (Martens and Wickens, 1995; and Yeh and Wickens, 2000) and decluttering through information removal (Mykityshyn, Kuchar, and Hansman, 1994) has shown that these techniques may be viable options for designers of cluttered displays.

In addition to the trade-offs themselves, designers must also be aware of how different tasks may affect pilot performance. Within the context of a navigation and hazard avoidance task, three different sub-tasks emerge: visual search, information readout, and information integration. Each of these sub-tasks involves a different type of attention and may be affected differently by the trade-offs of display integration.

When a pilot needs to find navigation information, the first thing he or she must do is locate the relevant information. Visual search is closely tied to (1) selective attention. Visual search performance is heavily driven by the number of objects within a display. In general, as the number of objects in a display increase, the response times of the searchers increase in a linear fashion (Neisser, Novick, and Lazar, 1964). The influence of database integration here is clear. When multiple displays are integrated the total number of objects in the resulting display, or global clutter, increases, which in turn could make locating information more difficult. As previously discussed however, the use of decluttering techniques may be able to mitigate the effects of the increased clutter.

Once the pilot has located the relevant information, he or she needs to read it. The readout sub-task utilizes (2) focused attention to filter out all the information except for the source relevant to the task. As with visual search, clutter influences the performance of this sub-task. In this case, however, it is the local density of information, or the number of objects adjacent to the object of interest, that may hinder performance. Again, by overlaying displays, the local density of any given object can potentially increase. This increase in local density, however, may be offset by the ability of the designer to display information at a greater resolution, as

well as making nearby items more discernable through use of different color or luminance level (i.e. highlighting).

Finally, after locating and reading the information, the pilot may need to integrate it with additional information. While visual search and readout always occur within the task, information integration only occurs when information from two or more domains must be compared or combined. Information integration requires (3) divided attention. Information integration sub-tasks may be positively benefited by display overlay. When pilots must view only one source of information instead of multiple ones, they have to perform fewer eye and head movements. In addition, the information is already spatially integrated, which may reduce errors of mental information integration. Such a benefit would not be observed for tasks requiring focused attention on one domain. This selective task specific benefit of overlay is more formally stated in the form of the proximity compatibility principle, or PCP (Wickens and Carswell, 1995).

The present experiment sought to quantify the effects of the design trade-offs associated with display integration within the context of a map task. Display integration was predicted to help performance when pilots were required to integrate information from two domains, while display separation was predicted to help performance when subjects had to only attend to one domain. Increasing the resolution of the displays was predicted to aid performance compared to a smaller display. Finally, decluttering was predicted to reduce the effects of the increased clutter caused by display overlay. Interactive clutter was predicted to yield higher accuracy, since the subject could control which aspect of the display was highlighted, but slower response times since the subject would be forced to interact with the system. Finally, lowlighting was predicted to be a more viable option than decluttering through information removal since subjects could view both domains.

## EXPERIMENTAL METHODS

Fifteen student pilots from the Institute of Aviation at the University of Illinois participated in an experiment to determine the relative costs and benefits of display integration. Subjects used six different display configurations (a large integrated, a small, separated side-by-side, a small integrated, a fixed lowlighting, an

interactive lowlighting, and an interactive decluttering display) to answer multiple-choice questions regarding two domains: navigation and air hazards. The navigation domain contained VFR maps scanned into the computer, while the air hazard domain was composed of traffic and weather information. Figure 1 shows a schematic diagram of the six displays.

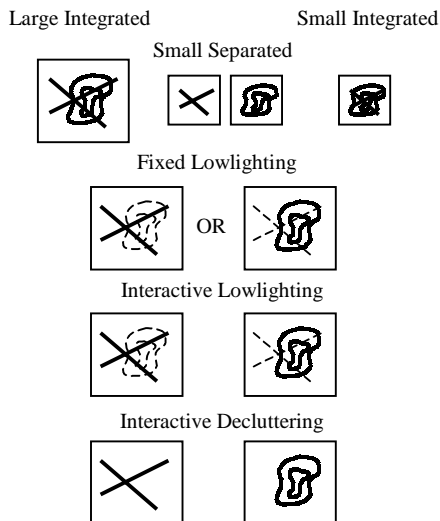


Figure 1. Schematic diagram of displays used in the experiment.

The two small displays were roughly one-fourth the area of the large displays. Lowlighting displays showed one domain brighter than the other, while the decluttering display showed only one domain at any given time. For the interactive displays, subjects were able to toggle back and forth between the two different database views by pressing the space bar. The experimental stimuli were presented by a Silicon Graphics O2 workstation with a 21-inch CRT monitor.

Focused attention questions required the subject to only search one domain (i.e. the navigation domain OR the air hazard domain) to answer a question. For example, the question "What is the altitude of flight X?" requires the subject to only attend to the air hazard domain. Divided attention questions required the subjects to integrate information from both domains. For example, "Will flight Y fly over a lake?" requires information from both the navigation domain and the air hazard domain.

The experiment consisted of six blocks of trials, each corresponding to a different display configuration. Each block of trials consisted of a practice trial and four experimental trials. Each

trial consisted of ten multiple-choice questions, half focused attention and half divided attention. Subjects answered the questions by pressing one of four keys. After an answer was recorded, the next question appeared until all ten questions were completed. At this point, another black screen would appear. There was no perceptible lag in the display and question presentation so neither of these stimuli was masked. The experiment took approximately one and one half hour to complete.

## RESULTS

Since this experiment sought to quantify several different aspects of display usage, separate repeated measures analyses of variance (ANOVAs) were performed on each aspect. A full version of the results can be found in Kroft and Wickens (2001).

To evaluate the effects of increased clutter due to display integration, performance using the large integrated display was compared to that using the small separated display. The analysis of RT showed pilots using the large display answered approximately 1 second faster than those using the separated display,  $F(1, 14) = 7.66, p < 0.05$ . However, the benefit of an integrated display was only seen for divided attention questions, while the displays did not differ for focused attention questions ( $F(1, 14) = 25.45, p < 0.01$ ), suggesting a cost for information integration when using separated displays.

The benefits of display separation for focused attention questions were reversed for divided attention questions,  $F(1, 14) = 18.21, p < 0.01$ . While the separated display produced more accurate results for focused attention questions, presumably due to the decreased level of clutter compared to the integrated display, performance was degraded when the subjects were required to mentally overlay information in order to answer the divided attention questions.

The extent to which the divided attention benefits of the integrated display for both RT and accuracy were due to a reduction in integration requirements achieved by the overlay or to the greater spatial resolution resulting from the larger screen size was assessed by a second ANOVA comparing the small integrated display with the small separated display, effectively controlling for resolution. The analysis found a

significant interaction of display and question type,  $F(1, 14) = 43.69$ ,  $p < 0.01$ , of the same form as that observed in the first analysis. The RT benefit of the separated display for focused attention questions is reversed for divided attention questions.

Analysis of the accuracy data showed that performance was 7% more accurate with the separate display ( $F(1, 14) = 15.82$ ,  $p < 0.01$ ), but an interaction between display size and question type ( $F(1, 14) = 10.85$ ,  $p < 0.01$ ) revealed that focused attention questions were answered with about 15% greater accuracy with the separated than the integrated display; whereas divided attention questions were answered with nearly equal accuracy for both display formats.

To examine the effects of resolution, a third ANOVA compared the large integrated display with the small integrated display. Responses were 1.5 seconds faster with the larger display,  $F(1, 14) = 16.61$ ,  $p < 0.01$ . An interaction between display and question type,  $F(1, 14) = 8.75$ ,  $p = 0.01$ , revealed that the benefit of larger resolution was amplified for focused attention questions. The large display supported approximately 12% greater accuracy than the small display,  $F(1, 14) = 7.38$ ,  $p < 0.05$ .

Finally, the effectiveness of the three decluttering displays was assessed by comparing the large integrated display (used here as a measure of baseline performance) with the fixed lowlighting, interactive lowlighting, and interactive decluttering displays in a fourth ANOVA. The analysis of the decluttering data revealed that the baseline display supported response times that were faster than each of the three other displays,  $F(3, 42) = 3.52$ ,  $p < 0.05$ . A significant interaction of display and question type,  $F(3, 42) = 3.67$ ,  $p < 0.05$ , revealed that the baseline display showed a benefit for divided attention questions, whereas the interactive decluttering display showed a large benefit for focused attention questions. The interactive decluttering display produced the most accurate responses, with the interactive lowlighting display showing the lowest accuracy,  $F(3, 42) = 2.46$ ,  $p = 0.08$ .

Finally, the analysis on the number of times subjects toggled between views in the two interactive display conditions showed a main effect of display type,  $F(1, 14) = 59.37$ ,  $p < 0.01$ . Subjects toggled about twice as much with

the decluttering display as expected since they could not see both domains at the same time. There was also a strong main effect of question type,  $F(1, 14) = 46.40$ ,  $p < 0.01$ , where divided attention questions induced more toggling. The interaction between the two factors,  $F(1, 14) = 52.26$ ,  $p < 0.01$  showed that the increase in toggling for the interactive decluttering display is most heavily driven by divided attention questions. Again, this is expected since using the interactive decluttering display required subjects to toggle at least once in order to see both domains. On the other hand, pilots should have to toggle less for focused attention questions since the correct domain should already be displayed half the time. Finally, when using the lowlighting display, pilots should not have to toggle at all since all the information is present in some form.

## DISCUSSION

One of the primary areas of interest in the experiment was the trade-off between reduced scanning and increased clutter, as seen in the analysis comparing the large integrated display with the small separated display. Our results suggest that the benefit of reduced scanning generally outweighs the cost of increased clutter. This effect was more pronounced for divided attention questions than for focused attention questions, as predicted by the proximity compatibility principle (Wickens and Carswell, 1995). Not only do the present results support the PCP, replicating previous findings by Wickens and Helleberg (1999) and O'Brien and Wickens (1997). Despite this, however, it is clear that increased clutter can hinder performance, as evidenced by the lower accuracy recorded for focused attention questions. Here, when the need to integrated information is eliminated, the increased clutter from the irrelevant domain hampers subject performance.

The previous comparison, however, is confounded by the effects of resolution. To eradicate this confound, a second analysis comparing the small integrated display to the small separated display was performed. When resolution is controlled for, a similar pattern of results still emerges. Here, there was a cost for database integration, in terms of response time and accuracy, for focused attention questions. On the other hand, the benefit for integration was only seen in RT for divided attention questions.

The effects of resolution on subject performance were also fairly straightforward. The larger display produced faster responses than the smaller display regardless of the task. That is, both divided and focused attention questions were answered more rapidly with the large display. In addition, the large display also produced higher accuracy, ruling out the possibility of a speed accuracy trade-off. We cannot, however, discern whether the cost attributed to reduced resolution is directly related to the smaller visual angle of the text to be read, or whether it is a result of the smaller visual angle that separates relevant from irrelevant information. To do so would require that display size be compared with non-overlaid displays, a condition not examined in this current experiment.

Given the observed advantages of integrated databases, we sought to further enhance performance through the use of lowlighting and decluttering techniques. Although previous research (Martens and Wickens, 1995; and Yeh and Wickens, 2000) showed a benefit for lowlighting irrelevant information, the current results did not replicate these findings. The fixed lowlighting display did not produce higher accuracy than the baseline large display, nor did it reduce subjects' response times. This lack of a benefit for lowlighting may be the result of a lack of readability of the lowlighted information, particularly when the ground symbology was lowlighted (Kroft and Wickens, 2001). This issue could be settled by future research comparing a display where both domains are lowlighted to the baseline display.

The other facet of the decluttering techniques reported here was the pilots' interaction with the displays. In two of the displays the subjects had the option to toggle back and forth between two views of the domains. In the lowlighting display, they could manipulate which domain was brighter and in the decluttering display, they could switch between views of one domain or the other. Our results showed a clear detriment for interactivity. The interactive display produced longer response times, a phenomenon directly related to the number of times subjects toggled between views. In addition, as would be expected, divided attention questions produced longer response times and more toggles than focused attention questions.

In addition, to the control condition for the lowlighting displays, several other venues for further research exist. First, by using eye-tracking, it would be possible to weigh the cost of scanning between displays against the cost of toggling between them. Second, the displays used here were static. By introducing dynamic displays, the effects of interactivity on situation awareness could be examined. Finally, the workload for the experimental task was relatively low. Subjects only had to answer questions with no primary or secondary task. By introducing the displays in the context of a flight task, the effects of integration could be further validated in a more "real world" environment.

## CONCLUSIONS

Database integration is a viable method for designers to display more information to pilots. By integrating displays, the required between-display scanning is reduced and the text and symbols of the display can be displayed at a higher resolution. This benefit, however, is somewhat dependant on the task. Integrated displays work best when information from different domains must be integrated. When only one domain must be attended to, the increased clutter of the integrated display can have adverse effects on performance. Finally, increased interactivity with the displays creates longer response times with no benefit for accuracy.

## ACKNOWLEDGMENTS

The experiment reported here was supported by a grant from NASA Ames Research Center #NASA NAG 2-1120. Dr. David Foyle was the scientific/technical monitor. Also, thanks go to Sharon Yeakel for her help in programming the experimental scenarios.

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