ADAPTIVE INFORMATION FUSION FOR SITUATION AWARENESS IN THE COCKPIT

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Evidence is provided pointing to potential caveats associated with the use of information fusion techniques in the cockpit. Six pilots each with a minimum of ten years flight experience completed a series of missions using a simulated future jet cockpit. Each trial required a pilot to guide their aircraft towards a fixed location. The pilot was required to estimate the position of this location both during and five minutes after the flight. Different types of fusion were manipulated with regard to the information presented on a touchscreen display – Fused, Fused Drill-Down, and UnFused. Data suggested that information fusion alone can have negative consequences for both task performance and subsequent recollection of information. It is argued that reductions in system transparency and transfer-appropriate processing may account for these findings.

INTRODUCTION

Information fusion techniques are often used by designers of complex systems such as those found in the cockpit, command and control scenarios, and process control plants. Defined as “synergy in the information acquired from multiple sources” (Dasarathy, 2001, p.75), the process of information fusion aims to present the operator with a more coherent picture by “cleaning up” the various streams of information available. In doing so, information fusion techniques aim to reduce the cognitive workload experienced by the operator when attempting to extract information from a system display. An example of this can be seen in the study conducted by Vicente, Moray, Lee, Rasmussen, Jones, Brock, & Djemil (1996). In evaluating the effectiveness of the Rankine Cycle Display for the monitoring and diagnosis of nuclear power plant status, Vicente et al., demonstrated significant benefits associated with a move away from the single-sensor single-indicator philosophy, towards a more integrated representation of information. Ultimately, the objective of information fusion is to reduce the cost associated with accessing and integrating information from a system display. Due to the largely heterogeneous multitask environment observed within the cockpit, reducing operator workload via techniques such as information fusion is an especially important challenge faced by the designers of aircraft displays (Wickens, 2002).

Duggan, Banbury, Howes, Patrick, & Waldron (2004), however, suggested that more sophisticated psychological theory is needed to fully appreciate and understand the consequences of information fusion for an operator’s situation awareness (SA). Here we are referring to SA as the acquisition of task-relevant information at the appropriate time. It is proposed that, under certain circumstances, fusion will lead to reduced levels of system transparency and an impoverished ability to retain information following task completion (see Bainbridge, 1987 for a discussion of this topic with reference to automation). The fusion process is intended to provide the operator with a fused end product and a coherent picture from which many sources of information have been pieced together. The drawback to this process is that the operator is often left unaware of the information source(s) and the nature of any processing already conducted upon this information. If unexpected/novel decisions are to be made based upon this information, leaving the operator ‘out of the loop’ during the fusion process may have negative consequences. Thus, when information from disparate sources is fused, it is important that useful information is not also discarded and that unfused information is made accessible if and when needed. We suggest that under certain situations operators would benefit from the facility to ‘drill-down’ into the fused information in order to understand and validate its source and nature. The consequences of ‘drilling down’ into fused information are predicted to be two-fold. Firstly, performance at the task in hand is likely to be improved if the operator has the ability to examine the unfused information. Secondly, playing an ‘active’ role in information foraging is likely to engage the operator in more task-relevant processing that should facilitate learning and subsequent recall.

Externally fusing information within an interface removes the need for the operator to internally fuse this information, thus freeing up cognitive resources for other tasks. However, knowledge in-the-world should not be presumed to be necessarily more efficacious than knowledge in-the-head. Across a range of tasks, relevant inference making or internal processing has been shown to improve subsequent task performance relative to a passive reliance upon equivalent information provided within the environment (e.g., Duggan & Payne, 2001; McNamara, Kintsch, Songer, & Kintsch, 1996; Palmiter, Elkerton, & Bagget, 1991). Indeed, Schmidt & Bjork (1992) reviewed work conducted on movement learning and human memory to demonstrate that it is not always the case that a manipulation that maximizes performance during the task will
also benefit the retention of this information over time. In fact, manipulations that degrade the ease of acquisition during the task can support the long-term retention of this information. For the accurate recollection of information processed during a task, it is important that the individual is engaged in transfer-appropriate processing during this stage. Schmidt & Bjork (1992) viewed retrieval practice during the task as a specific form of transfer-appropriate processing. For example, if information is not permanently available during a task or is presented in a random/variable fashion, the participant will receive practice during the task of forgetting and retrieving this information that will result in improved retrieval mechanisms at test. Cognitive load theory dictates that to circumvent the human processing capacity limitations, task situations should decrease extraneous cognitive load that is not relevant to learning yet “increase, within the limits of total available cognitive capacity, germane cognitive load which is directly relevant to learning” (van Merriënboer, Schuurman, Croock, & Paas, 2003, p.11).

We suggest that when task-relevant processing is used to develop knowledge in-the-head, this will lead to better SA than reliance upon knowledge in-the-world provided by fusion techniques. Importantly, what can be defined as task-relevant processing will necessarily depend upon the goals of the task. These may be specific to current task performance, long-term retention, or a compromise between the two. In collaboration with QinetiQ, Farnborough (UK) the Information Fusion Testbed (IFT) was used as a means of evaluating information fusion technologies in development and their consequences for operator awareness both during and subsequent to task completion.

METHOD

Participants
Six male pilots between 30 and 50 years of age, each with a minimum of ten years flight experience, took part in the study.

Materials
The IFT simulated a future jet cockpit including Head Up Display, aircraft controls and interactive touchscreen display. Flight missions were used in which the goal of the task was to navigate the aircraft within the defined area of responsibility (70 x 70 nautical miles) and estimate the position of a fixed location. For the purpose of this study, the touchscreen display contained a map of the terrain directly beneath the aircraft and displayed the results of the information fusion. The radar display (to the right of the touchscreen display) contained spokes that indicated direction but not range of location relative to the aircraft. The spokes were displayed for two seconds with an eight second interval between each display. A confederate aircraft flew next to the pilot’s aircraft maintaining a constant separation of ten nautical miles enabling information to be shared between the two platforms. The pilot’s and confederate’s aircraft were always situated at the bottom centre of the touchscreen display and a straight line from the pilot’s aircraft icon indicated the direction of movement. Communication was not possible between the pilot and confederate. The starting location of both aircraft and the position of the fixed location were varied systematically across trials.

Within the Fused display, system derived location estimations were displayed on the touchscreen as small red squares (see Figure 1a). In the Fused Drill-Down condition, pilots were also able to investigate the accuracy of an onscreen estimation by touching the red square on the display. This produced an ellipse around the red square indicating the area within which the location was positioned (see Figure 1b). This ellipse remained onscreen for two seconds and pilots were allowed to use this facility, when available, as much or as little as they felt necessary. The fusion algorithm continuously integrated information from the two aircraft concerning previous estimated locations in order to present a permanently visible location estimate onscreen. Where the data were not fused, only the sharing of radar information between the two platforms was possible. Thus, in the UnFused condition, information from the radar display from both the pilot’s and the confederate’s aircraft were displayed as spokes upon the touchscreen (see Figure 1c). The intersection of the spokes represented the location estimate. Consistent with the radar display these spokes were displayed for two seconds with an eight second interval between each display. These location estimates were updated throughout each trial and were dependent upon the relationship between the pilot’s and confederate’s aircraft and the fixed location. Pilots were informed that they could use these onscreen location estimations to guide their estimations as much or as little as they saw fit.

Design
The representation of sensor input within the interface was manipulated to create the three different fusion conditions (Fused, Fused Drill-Down, and UnFused). Each pilot received two trials of each condition in a different randomized order.

Procedure
Prior to starting the six experimental trials, three practice trials (one of each condition) were completed to familiarize pilots with the task and display formats. The route flown during each trial was under the control of the pilot. At distances of 50, 40, 35, 30 and 20 nautical miles from the location, the prompt “RESPOND NOW” appeared onscreen. Pilots were required to touch the screen to record their location estimate and say “response entered” when finished. Each trial terminated after a response was made to the fifth prompt. Five minutes after the end of each trial a paper map was given to pilots who were required to mark their location estimate from memory. During the five minutes
preceding this memory test, pilots were required to complete a subjective assessment of their performance on the preceding trial. The results from this questionnaire form part of a larger study and will not be discussed here.

(a) Fused

(b) Fused Drill-Down

(c) UnFused

Figure 1: Representation of Touchscreen Display with (a) Fused, (b) Fused Drill-Down, and (c) UnFused conditions. (Note: Screenshots taken from a simulation of IFT omitting maps used.)

RESULTS

Estimated Location

For prompts 1 and 2 a large number of locations were not correctly identified, thus to avoid empty cells only data from prompts 3, 4 and 5 were analyzed. A 3 (Prompt 3/4/5) x 3 (Fused/Fused Drill-Down/UnFused) ANOVA with repeated measures on both factors was conducted upon accuracy of location estimation. There was no main effect of Prompt, F(2, 10) = 2.10, p >.05 and no interaction with fused condition, F(2, 10) = 0.40, p >.05. Thus, Figure 2 displays accuracy of touchscreen estimations averaged across prompts 3-5. There was an overall effect of fusion across the three conditions, F(2, 10) = 38.21, p <.001. Planned comparisons between the individual levels of Fusion across all three prompts found that location estimations in the UnFused condition were less accurate than in both the Fused (p <.01) and the Fused Drill-Down conditions (p <.001). The Fused Drill-Down condition produced marginally (p <.08) more accurate estimations than the Fused condition.

Figure 2: Accuracy of Location Estimations both During (averaged across prompts 3-5) and After Flight as a function of Fusion condition. (Mean distance is difference between actual and estimated location.)

Recall of Location

Pilot’s recall of location is also displayed in Figure 2. A reciprocal transformation of recall estimations was used to correct for differences in variance between the Fusion conditions (see Howell, 1997, p.327 for a discussion of this procedure). A one way ANOVA (Fused/Fused Drill-Down/UnFused) was conducted upon the transformed data. (Non-transformed data is shown in Figure 2.) There was an overall effect of Fusion across the three conditions, F(2, 10) = 17.27, p <.01. Planned comparisons found that recall was more accurate in the Fused Drill-Down condition compared to both the Fused (p <.01) and UnFused conditions (p <.01). Although there was no significant difference between the Fused and UnFused conditions (p >.05),
DISCUSSION

Two main predictions were tested. Firstly, it was proposed that any benefit of fusion seen during task performance would be mediated by the operator’s ability to ‘drill-down’ into the fused information. As expected, during task performance pilots were more accurate in their location estimations when fusion was present compared to when it was not. Thus, information fusion improved the accuracy with which pilots could identify the position of the fixed location during the task. Included in the fusion algorithms was history information that allowed for the permanent presentation of system estimates onscreen. The lack of these benefits in the UnFused condition may have made the task of identifying location difficult. There will, for example, have been times in the UnFused condition when pilots were prompted to make a location estimation without the aid of onscreen location estimates. More interesting however, is the improvement in pilot’s estimation accuracy seen in the Fused Drill-Down condition compared to the Fused condition (although this effect was marginal). This can tentatively be taken as some support for one of the predictions made by Duggan et al., (2004) that in certain situations the fusion process can reduce SA through loss of system transparency.

It appears that pilots made good use of the ability to ‘drill-down’ into the fused information and that the extra information provided by this facility improved the accuracy of location estimations. Presumably pilots used the ellipses created in this condition to validate the accuracy of the Fused estimate, thereby increasing levels of inference making and reducing passive reliance upon the onscreen estimate. Although the temporary nature of the information provided in the UnFused condition may have also prompted high levels of inference making, these inferences are unlikely to have been as accurate as those made in the Fused Drill-Down condition. They were also less effective than relying upon onscreen system estimates provided in the Fused condition.

The second prediction was that any benefit of fusion alone during task performance may not be apparent at recall. Indeed, despite the fact that the Fused trials produced more accurate location estimations than the UnFused condition during the task, no significant difference was observed between the Fused and UnFused conditions at recall. In fact, the trend was reversed at this stage and five out of the six pilots produced more accurate estimations when recalling location information from UnFused trials. Although only at a descriptive level, this indicates that retention of information was superior in the UnFused compared to the Fused condition. One interpretation of this is that the temporary nature of the UnFused information resulted in pilots adopting qualitatively different strategies during the task compared to those strategies adopted as a result of the permanently available information provided in the Fused condition. Because onscreen location estimations were always present in the Fused condition, pilots may have relied more upon the display as an external memory source and less upon processes reliant upon internal memory. During periods in the UnFused condition where no onscreen information was provided, pilots may have engaged in retrieval strategies to try and retain location information.

Extrapolating from cognitive load theory, it would be expected that by increasing the reliance upon internal memory in the UnFused condition there would be an improvement in recall at test (van Merriënboer et al., 2003). Schmidt & Bjork (1992) specifically argued that information processing activities that cause forgetting of to-be-remembered information, and thus require practice at retrieving it again during the task, are beneficial for retention. If retention of information is a requirement following completion of the task, retrieval practice can be seen as a form of transfer-appropriate processing. The UnFused condition also required pilots to mentally integrate information from both aircraft (in the form of radar spokes). This integration of information was carried out by the fusion process in the Fused conditions and thus reduced the amount of internal processing needed to extract information from the Fused display.

In the Fused Drill-Down condition, decoding the extra location data provided by the ellipse would have necessitated further task-relevant information processing that may have also aided recall. Taken together, these findings provide support for suggestions made by Duggan et al., (2004) that relying upon the system display as an external memory source may subsequently retard performance in terms of internal memory for information presented. That is, if information is externally fused into the working environment, the associated reduction in reliance upon internal processing and memory strategies during task performance may have negative effects when information from the system display is to be recalled.

Of particular importance to the current study is what Herb Simon referred to as ‘informational equivalence’ (Larkin & Simon, 1987). There are obvious differences between the fusion conditions in terms of the nature of the information provided to pilots and the form in which it is represented. For academic and theoretical development, higher levels of informational and representational equivalence will be simulated. This will be the main thrust of future work to be conducted in a more controlled laboratory setting aiming to disentangle the effects seen so far. This study, however, was primarily interested in how experienced pilots would use the end product of fusion. From an applied perspective, we have learnt about the effectiveness of the fusion techniques evaluated in this study on task and recall performance (namely that Fused Drill-Down is most effective).
The conditions experienced by the pilots in this experiment reflect a very low level of workload. Different results are likely to be obtained if the pilot’s workload were to be increased. For example, perhaps the extra transfer-appropriate processing suggested to be happening in the UnFused condition would overload cognitive resources should the pilot be required to track and estimate the position of three locations per trial rather than just the one. A similar argument could be put forward if a multi-tasking environment were to be enforced where task allocation and the distribution of limited resources are critical (Wickens, 2002).

Pivotal to our argument here is the trade-off between increasing task-relevant processing for the benefit of task performance and reducing levels of cognitive workload to free limited resources for the attention of other wide-ranging tasks. The reduced cost associated with accessing information from a fused display will mean that the operator is better equipped to multi-task and extract the information needed quickly. However, the flip-side to this is that the information extracted from the fused display is likely to have received limited task-relevant processing and thus reduced system transparency and poor long-term retention are potential consequences. With this in mind, it is proposed that information fusion technologies need to be adaptive to the task they are designed to support and the level of workload experienced by the operator at different times. The system display should encourage as much task-relevant processing as is needed for the task in hand and is possible given the constraints of the overall workload experienced by the operator at that time.

In summary, preliminary evidence is provided of potential caveats associated with the use of information fusion in the cockpit. It has been demonstrated that the precise nature of information fusion and the circumstances under which operator performance is assessed will have varying consequences for an operator’s SA. From an applied perspective, it has been demonstrated that information fusion can have negative consequences for both task performance and subsequent recollection of information. From a theoretical perspective, system transparency and transfer-appropriate processing have been used to account for these findings respectively. Further experimental research aims to provide a tightly controlled environment in which to disentangle the theoretical underpinnings accounting for the effects seen thus far.

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REFERENCES


