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Designing information fusion for the encoding of visual-spatial information

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Three experiments investigated whether reduced cognitive processing associated with extracting information from a fused environment may lead to impoverished encoding of visual-spatial information. Experienced pilots and students completed various simulated flight missions, each requiring the use of dynamic onscreen information under Fused and UnFused conditions to estimate the position of a number of locations. Following a retention interval, memory for locations was assessed. Experiment 1 demonstrated that the retention of fused information was problematic in an applied setting, and Experiment 2 replicated this finding under laboratory conditions. Experiment 3 successfully improved the retention of Fused information by limiting its availability within the interface, which shifted participant's strategies from over-reliance upon the display as an external memory source, towards more memory-dependent interaction. These results are discussed within the context of intelligent interface design and effective human-computer interaction.

1. Introduction

Operators of complex systems, such as those found in the modern aircraft cockpit, have access to an unprecedented volume of information, originating from a variety of on- and off-board sensors. The problem faced by the Human Factors and Ergonomics community, therefore, is how best to organise and present such an abundance of information without inducing 'information overload' (Woods, Patterson, and Roth 2002). Defined as synergy in the information acquired from multiple sources (Dasarthy 2001), information fusion techniques aim to reduce the cost associated with accessing and integrating information from the task environment. In doing so, it is possible that the operator's task of information extraction and assimilation is made easier and more effortless. However, it is necessary to investigate cost-benefit trade-offs and whether boundary conditions exist such that performance on certain task criteria may be degraded. Specifically, we suggest that the manner in which information is presented within a fused environment may have negative consequences for the encoding of visual-spatial information.

1.1. Information fusion – a contemporary solution to information overload

Ultimately, information fusion aims to reduce the cost associated with accessing information from the interface. This principle can also be seen in a variety of more established approaches to cognitive engineering (e.g. Ecological Interface Design - Vicente and Rasmussen 1992, Representation Aiding - Woods 1991, Configural Displays - Bennett and Flach 1992, Proximity Compatibility Principle - Wickens and Carswell 1995), with many examples designed to meet the demands of particular task

criteria. However, use of the term information fusion in the present article is not intended to extend to the often complex process by which such approaches attempt to provide operators with higher-order functional information within a specific unified display. Instead, our investigation and discussion of information fusion focuses on the often generic side effects associated with decreasing the cognitive processing associated with extracting information from the interface (e.g. Gray, Simms, Fu, and Schoelles 2006).

By integrating information from a number of different sources, information fusion reflects a movement away from traditional single-sensor single-display design, whereby each display represents the value of a single measurement (Woods 1991). In such environments the operator is required to sequentially gather the information needed from individual instruments (often spatially separate), maintain this information in memory, and mentally integrate the information collected to arrive at a decision. These processes of information gathering and integration can impose high, sometimes overwhelming cognitive demands upon the operator, taxing limited resources such as attention and memory (Wickens 1992).

Comparisons between integrated and single-sensor single-display design have been conducted in a number of environments (e.g. Pawlak and Vicente 1996, Vicente, Moray, Lee, Rasmussen, Jones, Brock, and Djemil 1996, Marino and Mahan 2005), including aviation (e.g. Dinadis and Vicente 1999, Lintern, Waite, and Talleur 1999), and have demonstrated benefits derived from integrated displays in supporting user decision making. In their comprehensive review of graphical displays, Bennett and Flach (1992) acknowledge that 'there appears to be a clear consensus that performance can be improved by providing displays that allow the observer to utilize the more efficient processes of perception and pattern recognition instead of requiring

the observer to utilize the cognitively intensive processes of memory, integration, and inference' (p.514).

There are, however, potential shortcomings associated with attempting to provide the operator with the information they need via intelligent displays. This has been well documented in the automation literature, (see Parasuraman and Riley 1997 for a review), with negative effects including the lack of system transparency, and the failure to keep the operator 'in the loop' (Bainbridge 1987). It is argued here that there may be similar potential problems associated with providing the operator with fused information. Making information too accessible via the process of fusion may increase an operator's reliance upon the external display, and thus, reduce the extent to which the information presented is internalised. (See Waldron, Duggan, Patrick, Banbury, and Howes 2005 for an applied demonstration of such a concern.)

The general philosophy during assessment of display design is not to evaluate a display based upon the extent to which it promotes the internalisation of information presented within the external display, but rather, to focus upon the effectiveness of the display in supporting the operator during information extraction and decision making. However, some work has investigated the value of using memory as a methodology for evaluating display effectiveness (e.g. Vicente 1992), and has proposed that the use of memory to evaluate display effectiveness is better suited to analyses of semantically meaningful variables, as opposed to detailed visual information (Sperling 1960). For this reason, the current article will focus on display design intended to provide the operator with visual-spatial information that does contain semantic content.

1.2. Psychological consequences of increased accessibility of information

What follows is a brief review of relevant psychological literature suggesting that reducing the cognitive processing required to extract information from a fused environment may have negative consequences for the encoding of such information. Firstly, work is cited highlighting the importance of display design in promoting active engagement (on behalf of the operator) in processes that make use of memory and inference making (e.g. McNamara, Kintsch, Songer, and Kintsch 1996, Gray et al. 2006), which contribute to the development of a robust internal representation of the task environment, and can thus be seen as 'transfer-appropriate processing' (Morris, Bransford, and Franks 1977), when memory for visual-spatial information is important. Secondly, a proposal is made that the use of information fusion will, in some situations, reduce the extent to which operators of complex systems engage in such transfer-appropriate processing.

Experimental research has shown that even very small changes to the design of an interface can significantly affect the extent to which internal memory is deployed during interactive behaviour. For example, by increasing the cost of accessing information from a simple eye movement to a head movement, Ballard, Hayhoe, and Pelz (1995) induced a shift in participants' behaviour from a largely display-based strategy to one more reliant upon working memory. Work continuing in this theme has indicated that the lower the cost associated with accessing information from a display, the less likely participants are to employ memory-intensive strategies during both routine interactive behaviour (Fu and Gray 2000; Gray and Fu 2004; Gray et al. 2006) and problem solving (Waldron, Patrick, Howes, and Duggan 2006). If information is readily available in-the-world, a shift is often observed from memory-

intensive strategies to more display-based ones, often referred to as perceptual-motor strategies (see Gray et al. 2006). Hence, the individual may rely upon the display as an external memory source (O'Regan 1992). It follows then, that the use of internal memory by operators of complex systems may decrease as the cost associated with accessing and integrating information from the task environment is reduced via information fusion. This reduction in the use of memory during information extraction from a fused display is likely to have negative consequences for the retention of visually presented information. Indeed, the frequency with which different memory traces are called upon is integral to many theories of declarative memory (e.g. Anderson and Milson 1989).

In their discussion of the adaptive nature of memory, Anderson and colleagues (Anderson and Milson 1989, Anderson and Schooler 1991, Anderson, Fincham, and Douglass 1999) have argued that activation of a memory trace is, at least in part, determined by retrieval practice. They propose that the human memory system has the form it does so as to make more available memories that are used more often in the past (the practice effect). It has also been suggested that memory's most apparent deficit, forgetting, may in fact be an adaptive response to the need to focus on currently available information (Anderson and Milson 1989, Bjork and Bjork 1992). Functional decay theory proposes that when a task requires memory to be updated frequently, decay must occur to prevent interference with later memories (Venturino 1997, Altmann and Gray 2002). It is quite probable, therefore, that a reduction in the use of memory during information extraction (as a result of information fusion) will have negative consequences for the retention of visual-spatial information.

There is also a wealth of knowledge suggesting that relevant internal processing improves subsequent task performance relative to a passive reliance upon equivalent

information provided within the environment (e.g. Palmiter, Elkerton, and Bagget 1991, McNamara et al. 1996, Duggan and Payne 2001). The idea that the encoding of information can be improved via relevant processing can be dated back to the seminal 'levels of processing framework' developed by Craik and Lockhart (1972). Also the inserted questions literature (e.g. Glover 1989) and the text comprehension literature (e.g. McNamara, et al. 1996) have demonstrated that prompting participants to make task-related inferences whilst reading text can aid the comprehension and retention of text. Using the everyday task of programming a VCR, Duggan and Payne (2001) improved participants' retention of instructional information by prompting them to adopt a chunked instruction-following procedure (reliant upon memory). By reading and then performing several steps of the programming cycle at a time (compared to one step at a time), participants were engaged in more internal processing during the training phase and consequently outperformed the 'one step at a time' group at test.

Engaging individuals in task-relevant inference making and memory-intensive strategies during task performance can be seen as an example of what Morris et al (1977) coined 'transfer-appropriate processing'. In essence, transfer-appropriate processing theory states that matching the cognitive demands during learning with those observed at retrieval gives rise to better retention than mismatched learning and retrieval conditions. 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 subsequently retrieving this information. Consequently, retrieval mechanisms will have been practised and therefore available at test. Relatedly, it is not always the case that a manipulation that maximizes performance during the task will also benefit the retention of task-related information over time. In fact, manipulations that degrade the ease of acquisition during the task

can often support the long-term retention of this information (Schmidt and Bjork 1992). Following from cognitive load theory (Sweller 1988, Chandler and Sweller 1996), it has been recognised that so-called 'germane cognitive load' (van Merriënboer, Schuurman, de Croock, and Paas 2002) facilitates learning. Therefore it could be predicted that, within the limits of total available cognitive capacity, increased processing load associated with the extraction of information presented within an external display will facilitate the learning and therefore retention of visual-spatial information.

Based upon the assumption that reducing the cost of accessing information within an interface will reduce the use of memory-intensive strategies during information seeking (e.g. Gray et al. 2006), and the assumption that relevant internal processing (e.g. Anderson and Milson 1989, McNamara et al. 1996) is required to maintain and update memory during interactive behaviour, we predict that under certain circumstances the use of information fusion may lead to impoverished encoding and poor retention of information presented within an external display. In order to test this hypothesis, the effectiveness of a fused and unfused cockpit display will be evaluated in terms of supporting operator performance, both during simulated flight missions, and when recalling mission information. A high-fidelity flight simulator was used in Experiment 1 to assess and compare the effectiveness of fusion technologies currently in development against more traditional unfused displays. Further studies (Experiments 2 and 3) were conducted using a low-fidelity simulation in an attempt to replicate and differentiate, under laboratory conditions, between explanations responsible for the results observed in Experiment 1.

2. Experimental task

Flight missions were used in which the goal of the task was to navigate the aircraft within an area of interest and estimate the position of a number of fixed locations (1, 2, or 3). For all experiments, the area of interest was represented by a 70 x 70 nautical mile (nm) terrain map. Although participants were never informed of the actual position of the location(s), dynamic indirect estimates of location position were provided within the interface in order to guide estimation. Following completion of each flight mission, participants' memory for location position(s) was tested. Contained within every square nm of the terrain map were a number of landmarks, and thus memory for location information involved semantic properties and relational information.

During each flight mission a confederate aircraft flew alongside the participant's aircraft maintaining a constant separation of 10 nm, enabling information to be shared between the two platforms. The extent to which this information was fused within the interface was the focal point of the first two experiments, with the final experiment concentrating on the effects of manipulating the temporal availability of fused information. Both fused and unfused displays contained radar information indicating direction but not range of location(s) relative to the participant's aircraft (see Figure 1). The representation and availability of dynamic location information projected onto the terrain map, however, differed according to whether fusion was, or was not present.

[Insert Figure 1 about here]

Within the fused display, shared location estimates were displayed onscreen as small squares (see Figure 1a), which were permanently available onscreen (representing an estimation of both direction and range of location positioning). In the unfused display, information from the radar display from both the pilot and the confederate aircraft was presented as individual spokes onscreen (see Figure 1b). Each relevant intersection between corresponding spokes represented an estimation of both direction and range of location position(s). Consistent with the radar display, these spokes were available onscreen for two seconds, with an eight second interval between each display (during which no information was available onscreen). These dynamic onscreen location estimates were updated throughout each trial and were dependent upon the relationship between pilot and confederate aircraft and the fixed location(s). Participants were informed that the onscreen estimates would never be 100% accurate, would move around, and that they could use this information to guide their location estimations.

3. Experiment 1

The Information Fusion Testbed (IFT) located at QinetiQ, Farnborough, was used in Experiment 1 to test the hypothesis that, when compared to a more traditional unfused display, a novel fused display would support operator performance during flight missions, yet lead to impoverished encoding and subsequent retention of location information. Specifically, it was predicted that the use of fusion to provide operators with permanently available onscreen information (in the form of small squares) would lead to over-reliance on the external display, and a lack of transfer-appropriate processing. In contrast, the semi-permanent nature of information provided within the

unfused display (in the form of spoke intersections) was predicted to promote the use of memory and inference making during flight missions, thus improving the encoding and retention of location information.

3.1. Method

3.1.1. Participants. Participants were six male pilots between 30 and 50 years of age, each with a minimum of ten years flight experience.

3.1.2. Materials. The IFT simulated a high fidelity future jet cockpit including Head-Up Display, aircraft controls and interactive touchscreen display. Contained within the touchscreen display was the radar and terrain display. Information provided within the radar display became active when the participant's aircraft flew within 55 nm of the location(s).

3.1.3. Design. The representation and availability of information provided within the terrain display differed according to whether it was Fused or UnFused and was manipulated within-subjects. The fusion algorithm continuously integrated information from the two aircraft, whilst taking into account previous estimations in order to provide permanent onscreen location information. The Fused display became active when both aircraft flew within 55 nm of the location(s), and location estimates were in the form of small squares (see Figure 1). In the UnFused condition, however, only the sharing of semi-permanent radar information between the two platforms was possible. As with the radar display, UnFused spokes became active the moment either of the respective aircraft flew within 55 nm of the location(s), and location estimates were determined by the relevant intersections between corresponding spokes.

Consistent with the radar display, these spokes were displayed for two seconds with an eight second interval between each display. The number of locations (1, 2, or 3) was also manipulated within-subjects to create three workload conditions. On occasions where more than one location was to be identified, each of the locations was situated within 10 nm of one another. The starting location of both aircraft and the actual position of each location varied systematically across trials. Each participant received two trials from each treatment combination in a different randomised order.

3.1.4. Procedure. Prior to the commencement of twelve experimental trials, two practice trials were completed to familiarise participants with the task and display formats. Each trial consisted of one flight mission, retention interval and recall test. The route flown during each mission was under the control of participants at all times, and because performance was likely to vary over the duration of flight, measures were taken at several points to observe both the development of location accuracy over time and any interaction with fusion. At distances of 50, 40, 35, 30 and 20 nm from the location, the prompt 'RESPOND NOW' appeared onscreen at which point participants were required to touch the screen to record each location estimate. Each flight mission terminated once a response had been made to the final prompt. Recall of location(s) was also measured five minutes following the completion of each flight mission. A paper map was given to participants to mark their location estimates. During the five minutes preceding this memory test, participants were required to complete a subjective assessment of their performance on the preceding flight mission.

3.2. Results

A number of rules were implemented during the analysis of these data. Firstly, if the number of responses made by the participant ever exceeded the number of responses required, the response(s) nearest the actual location(s) was taken. Secondly, any 'no-responses' resulted in missing data points. Two methods were used to measure participant's location estimates. Measure 1 matched a participant's location estimate(s) to the actual location(s) position in such a way so as to minimise the total mean distance error. Measure 2 matched the centre of a participant's location estimate(s) to the centre of the actual location(s). Minimal differences were observed as a function of these two measures, and thus, only results obtained via measure 1 will be reported. Upon violations of sphericity, Greenhouse-Geisser corrected degrees of freedom are reported, and non-transformed data are presented in tabular and graphical format. The effects of fusion and workload on location accuracy during a flight mission will be reported first, followed by the effects of fusion on the retention of location information.

3.2.1. Location accuracy. For prompts 1 and 2, over 50% of locations were not correctly identified. Thus, to avoid empty cells only data from prompts 3, 4 and 5 were analysed. A log transformation was performed on the data in order to correct for differences in variance between the fusion conditions, and a 3 (Prompt 3/4/5) x 2 (Fused/UnFused) x 3 (Locations 1/2/3) within-subjects ANOVA was computed on the transformed data. The Fused condition yielded significantly more accurate estimations than the UnFused condition, $F(1, 5) = 47.36$, $p < .001$, $MSE = 0.04$, and estimations became less accurate as the number of locations increased, $F(2, 10) = 12.20$, $p < .01$, $MSE = 0.02$. A significant interaction was observed between fusion x locations, $F(2,$

10) = 11.60, $p < .001$, $MSE = 0.04$, with simple main effects revealing an advantage for Fused over UnFused when there were two locations, $F(1, 5) = 102.71$, $p < .001$, or three, $F(1, 5) = 19.69$, $p < .05$, but not when there was one, $F(1, 5) = 0.99$, $p > .05$ (see Table 1). No main effect of prompt was observed, $F(2, 10) = 0.60$, $p > .05$, $MSE = 0.03$, and participants in each of the fusion conditions were equally accurate in identifying the correct number of locations on each trial, as indicated by identical proportional means (Fused $M = 0.83$, $SD = 0.21$, UnFused $M = 0.83$, $SD = 0.24$).

[Insert Table 1 about here]

3.2.2. Location retention. Delayed location recall was compared against the immediate location estimations provided at the final prompt in order to examine the retention of location information following the retention interval. A reciprocal transformation was performed on the data in order to correct for differences in variance between the fusion conditions, and a 2 (Fused/UnFused) x 2 (Immediate/Delayed) x 3 (Locations 1/2/3) within-subjects ANOVA was computed on the transformed data. Overall, the Fused condition yielded significantly more accurate estimates than the UnFused condition, $F(1, 5) = 20.08$, $p < .01$, $MSE = 0.05$, and accuracy deteriorated during the retention interval, $F(1, 5) = 6.55$, $p < .05$, $MSE = 0.10$. Importantly, a retention interval x fusion interaction was found, $F(1, 5) = 7.76$, $p < .05$, $MSE = 0.07$, (see Figure 2) and simple main effects indicated that only at the final prompt (immediate) were estimations more accurate in the Fused, compared to the UnFused condition, $F(1, 5) = 20.30$, $p < .01$. No significant difference was

observed between Fused and UnFused at delayed recall, $F(1, 5) = 1.22$, $p > .05$.

Simple main effects also indicated that significant deterioration in accuracy occurred

in the Fused, $F(1, 5) = 7.42$, $p < .05$, but not in the UnFused condition, $F(1, 5) = 0.31$,

$p > .05$. A separate one way ANOVA conducted on proportional data found no

significant differences between the two fusion conditions in terms of recalling the

correct number of locations for each trial, $F(1, 5) = 0.17$, $p > .05$, $MSE = 0.01$.

[Insert Figure 2 about here]

3.3. Discussion

The two main predictions were supported. Firstly, during flight missions participants

were more accurate in identifying location position when fusion was present,

compared to when it was not. Secondly, deterioration of accuracy following the

retention interval was greater in the Fused, compared to the UnFused condition. Our

interpretation of the data is based upon the premise that more cognitive processing

was required to extract information from the UnFused, compared to the Fused display.

It is proposed that differences in the cognitive processing associated with extracting

information from the two displays explain both the superiority of the Fused display at

supporting the accurate estimate of locations during flight, and the impoverished

retention of location information derived from the Fused display.

Given the growing body of knowledge suggesting that making information more

accessible within the interface via integrated displays can facilitate information

extraction and decision making (e.g. Woods 1991, Vicente et al. 1996, Lintern et al.

1999), it is not surprising that the permanently available integrated location information provided within the Fused display led to more accurate location estimation than the provision of semi-permanent non-integrated location information provided within the UnFused display. As expected, with increasing workload the Fused display resulted in superior location accuracy during the flight, presumably reflecting the competing demands for limited resources, a finding consistent with the workload literature (Wickens 2002).

It is somewhat counterintuitive, however, that by increasing the availability of information provided within the interface, the Fused display also yielded a disproportionate rate of forgetting, when compared to the UnFused display. There are perhaps two explanations for this. Firstly, the permanent nature of onscreen information provided within the Fused display may have increased pilot's reliance upon the interface as an external memory source (O'Regan 1992, Gray and Fu 2004, Gray et al. 2006), and in doing so, rendered internal processing involving memory and inference making redundant. Similar arguments can be found within the training literature whereby the provision of concurrent visual feedback within an external display can act as a temporary crutch to performance, and subsequently lead to a decrement in retention of skill over time (e.g. Patrick and Mutlusoy 1982, Schmidt and Wulf 1997). Continuous feedback within a learning environment is often found to be effective during the learning phase because it guides the individual towards the required responses and reduces errors. However, many studies have also found that performance gains during practice are seldom observed at transfer tests when augmented feedback is withdrawn (see Patrick 1992 for a review). Although the onscreen information provided within the Fused display provided pilots with guidance information rather than feedback relating to performance, similar mechanisms are

proposed to account for the problematic retention of Fused information in the current study. Over-reliance upon display support may be detrimental to retention.

Secondly, the semi-permanent nature of location information provided within the UnFused display, on the other hand, is likely to have encouraged the use of internal memory and inference-making strategies in order to maintain an understanding of location position(s) during times when location information was not available onscreen. As previously emphasised, the use of internal processes such as memory and inference making during task performance are integral to the effective retention of task-relevant information (Anderson and Milson 1989, Schmidt and Bjork 1992, McNamara et al. 1996). A further issue concerns the additional cognitive processing necessary to integrate and distinguish between meaningful and coincidental spoke intersections provided within the UnFused display. The task of integrating and distinguishing between meaningful and coincidental intersections will necessarily have oriented pilot behaviour towards inference making, which may have acted as transfer-appropriate processing (Morris et al 1977, McNamara et al 1996) when considering the demands of the recall task Whilst this might contribute to the superiority of the UnFused display at retention, this may also have handicapped estimates of location during the flight.

The limitation of Experiment 1 is primarily that it is an applied study and as a consequence there are potentially confounding differences between the Fused and UnFused conditions, some of which have already been discussed in the context of different explanations for the results. There is a lack of representational equivalence (Larkin and Simon 1987) between the conditions, although from an applied perspective this is to some extent inevitable because a fused display for obvious reasons is never likely to adopt the physical characteristics of a radar display. In

addition, there are small differences in the nature of the algorithms underlying the provision of information between the two displays. Therefore, the overall goal of Experiment 2 was not only to remove these algorithmic differences between the Fused and UnFused displays, but also to attempt to replicate the main results of Experiment 1 under laboratory conditions using a low-fidelity simulation of the IFT. Experiment 3 investigated the importance of the temporal availability of displayed information, which has been discussed above as a factor that may affect cognitive processing. Given that the permanence of information in the fused display may have reduced cognitive processing and thus recall, Experiment 3 attempted to mitigate this effect by varying the temporal availability of fused information.

4. Experiment 2

Small, but significant discrepancies between the Fused and UnFused displays in Experiment 1 may have led to subtle differences between the conditions with regard to the accuracy of onscreen information at different points in time. For example, the algorithm used to produce the onscreen location information provided within the Fused display in Experiment 1 integrated previous information regarding the positioning of a particular location when updating information pertaining to that location. The onscreen estimates provided within the UnFused display, however, relied completely upon radar information, and consequently did not take into account previous location information when updating position estimates. There will also have been slight inherent delays in the onset of onscreen location information in the Fused condition. This was because the Fused algorithm required both the pilot and confederate aircraft to be within 55 nm of the location(s) before onscreen estimates

could be made available within the interface. In contrast, as soon as either aircraft in the UnFused condition flew within 55 nm of the location(s), information in the form of a single spoke was emitted from that aircraft (regardless of the status of the other aircraft).

Although the slight time delay and integration of location history information were inherent to the fusion technology under investigation in Experiment 1, it is important that both are removed in order to ensure the effects observed were attributable to the cognitive processing required to extract information from the interface, rather than differences between the fusion conditions in terms of accuracy of onscreen location information and the point at which such information became active. Therefore, Experiment 2 was conducted under laboratory conditions using a low-fidelity simulation of the IFT task (IFTsim).

4.1. Method

4.1.1. Participants. Participants were 42 Cardiff University students between 18 and 30 years of age. Each was paid £5 or received course credit for their participation.

4.1.2. Materials. IFTsim was written in *Visual Basic 6.0* and was presented to participants via a 12 x 13 inch high-resolution monitor and Pentium IV 2 Ghz PC. Both aircraft were set to travel at a constant speed, (simulating the average speed in the IFT), and the participant's aircraft was guided via left and right arrow keys on the keyboard. On each occasion an arrow key was pressed, the participant's aircraft would change its current heading by 22.5° in the corresponding direction. The confederate aircraft was always positioned 10 nm west of the participant's aircraft.

The starting location of both aircraft and the position of the fixed location(s) were varied systematically across trials.

The same algorithm was used to produce the onscreen location information in both fusion conditions. The nature of the algorithm meant that onscreen location information became more accurate as the aircraft grew closer to the actual location(s), and became active the moment the participant's aircraft flew within 55 nm of the actual location(s). Each onscreen estimate was updated in a unique fashion, four times per flight mission at distances of 50, 40, 30, and 20 nm from the actual location(s). Participants were prompted in the same manner as Experiment 1 to make their responses, although responses were made via mouse clicks on the screen rather than touchscreen responses, and only four were required per flight mission.

4.1.3. Design and procedure. These were the same as Experiment 1, with the exception that the number of locations was either one or three. At the recall stage of each trial, the map was presented on the computer screen and responses were made via mouse clicks. Each participant received one of four randomised trial orders so as to minimise the contribution of any idiosyncratic order effects.

4.2. Results

4.2.1. Location accuracy. A 4 (Prompt 1/2/3/4) x 2 (Fused/UnFused) x 2 (Locations 1/3) within-subjects ANOVA was computed upon non-transformed data. As in Experiment 1, participants in the current experiment revealed more accurate location estimation when working with the Fused, compared to the UnFused display, $F(1, 41) = 5.446$, $p < .05$, $MSE = 6.08$, and when there was one, compared to three locations to-be-identified, $F(1, 41) = 41.02$, $p < .001$, $MSE = 4.43$. Simple main effects examining

a fusion x prompt interaction, $F(3, 123) = 6.10$, $p < .001$, $MSE = 17.92$, revealed that the only benefit of Fused over UnFused occurred at the final prompt, $F(1, 41) = 35.92$, $p < .001$ (Fused *Mean Error* = 2.79, *SD* = 0.94; UnFused *Mean Error* = 4.60, *SD* = 2.61). Simple main effects were used to explore a fusion x location interaction, $F(1, 41) = 22.10$, $p < .001$, $MSE = 7.43$, and indicated that estimates in the UnFused condition became less accurate as the number of locations increased, $F(1, 41) = 40.26$, $p < .001$, whereas the Fused condition was relatively unaffected by the number of locations to-be-identified, $F(1, 41) = 2.70$, $p > .05$, (see Table 2). Again, no significant differences were found between the two fusion conditions in terms of identifying the correct number of locations on each trial, $F(1, 41) = 2.29$, $p > .05$, $MSE = 0.05$.

[Insert Table 2 about here]

4.2.2. Location retention. A 2 (Fused/UnFused) x 2 (Immediate/Delayed) x 2 (Locations 1/3) within-subjects ANOVA compared accuracy of delayed recall with immediate accuracy at the final prompt for both fusion conditions. A log transformation was required to correct for differences in variance between the fusion conditions. As with Experiment 1, the Fused display was found to yield more accurate estimations than the UnFused, $F(1, 41) = 25.06$, $p < .001$, $MSE = 0.02$, and accuracy deteriorated during the retention interval, $F(1, 41) = 56.48$, $p < .001$, $MSE = 0.05$. Importantly, a retention time x fusion interaction was found, $F(1, 41) = 11.80$, $p < .001$, $MSE = 0.03$, (see Figure 3), and again simple main effects indicated that

estimations derived from the Fused display were superior when immediate estimations were taken at the final prompt, $F(1, 41) = 39.26$, $p < .001$, but that there was no difference between the two fusion conditions at delayed recall, $F(1, 41) = 0.03$, $p > .05$. In contrast to Experiment 1 however, a decrement to location accuracy was witnessed as a function of retention interval for both the Fused and UnFused conditions ($ps < .01$).

[Insert Figure 3 about here]

Similar values observed at recall for the two fusion conditions may imply that a floor effect could be distorting the data. However, further examination in accordance with a criterion proposed by Cohen (1995) suggested this was not the case. The average recall values for both the Fused and UnFused conditions were sufficiently different to the average maximum recall error, indicating that performance was not at a floor. In addition, the considerable difference in the simple effect F values for the effect of retention interval on location accuracy was over twice that for the Fused condition, compared to the UnFused condition, suggesting a greater deterioration over the retention interval in the Fused condition. This interpretation is confirmed by an analysis of effect size that indicated a substantially larger effect in the Fused, compared to the UnFused condition (partial eta squared, 0.54 versus 0.34 respectively).

Again, no significant differences were observed between the two fusion conditions in terms of recalling the correct number of locations on each trial F (1, 41) = 1.89, $p >.05$, $MSE = 0.07$.

4.3. Discussion

Manipulation of fusion and workload affected task performance in much the same way as that observed in Experiment 1. The Fused display improved location accuracy relative to the UnFused display during flight missions, again supporting previous work (e.g. Woods 1991, Vicente et al. 1996, Lintern et al. 1999) suggesting that the provision of highly accessible integrated information can support operator decision making. However, unlike Experiment 1 where there was no decrement in UnFused information over the retention interval, in this experiment both Fused and UnFused information deteriorated. Nevertheless, there appeared to be a greater decrement in the Fused condition, as indicated by the interaction effect, and also by the different effect sizes. Location accuracy also reduced as the number of locations to-be-identified increased from one to three.

Naïve participants were used in Experiment 2, in contrast to the experienced pilots in Experiment 1. Although previous work (e.g. Mosier, Skitka, Burdick, and Heers 1996) has found student and experienced pilot samples to be equally susceptible to automation bias (that is, over-reliance upon automated information), participants in the current experiment found the estimation of three locations particularly difficult when working with an UnFused display. In contrast, the effect of workload on location accuracy during Experiment 1 was approximately equivalent across fusion conditions, and may reflect pilot expertise associated with distinguishing between meaningful and coincidental UnFused intersections.

Given the superiority of the Fused display at supporting the accurate estimation of locations during flight missions, it is striking that this did not translate to better memory for location positioning following the retention interval. Indeed, the disproportionate rate of forgetting observed in the Fused condition suggests that there is scope for improving the retention of fused information in the current task. From an applied perspective the important goal is to find a means of mitigating this effect and supporting the retention of fused information. Our previous discussion suggested that the decrement in Fused recall may be due to a lack of cognitive processing due to an over-reliance upon the display as an external memory source (O'Regan 1992). In contrast, the semi-permanence of information in the UnFused display may have resulted in memory-intensive processing. This perspective is consistent with Gray and colleague's (Fu & Gray 2000, Gray & Fu 2004, Gray et al. 2006) distinction between external display-based versus internal memory-based interaction strategies. Therefore, paradoxically, in Experiment 3 we investigate a method for improving the retention of fused information that involves reducing its availability within the interface.

5. Experiment 3

Reducing the temporal availability of location information provided within the interface is explored in the final experiment as a possible method for improving memory for Fused information in the current task. There are two possible explanations why this might be effective. Firstly, as discussed previously, when information is less available within an interface stronger reliance upon internal processing is induced, including memory and inferencing (O'Regan 1992, McNamara et al. 1996, Duggan and Payne 2001, Gray and Fu 2004, Gray et al. 2006). Secondly,

the on/off-set of visually presented information may lead to attentional capture, as seen in visual monitoring tasks (Yantis 1993, Sutcliffe 1995, Yantis and Jonides 1996). The former explanation predicts that the *duration* with which fused information is made unavailable will determine its retention, as opposed to the latter explanation, that predicts improvements will be a function of on/off-set *frequency*.

In order to evaluate these competing interpretations of any effect of reducing the availability of fused information, four conditions were employed in Experiment 3. Three conditions in which Fused information was provided in a semi-permanent fashion within every ten second cycle (on2off8, on8off2, on1off4) were compared to a Fused condition in which information was permanently provided within the interface (on10). If reducing the availability of Fused information does have the desired effect, these conditions allow the relative influence of the duration and frequency with which onscreen information was provided within the Fused display to be investigated.

5.1. Method

5.1.1. Participants. Participants were 80 Cardiff University students, between 18 and 30 years of age. Each was paid £5 or received course credit for their participation. One participant in the on2off8 condition was excluded due to obtaining a z-score of 4.08 (see Field, 2005).

5.1.2. Design. The temporal availability of onscreen location information was manipulated between-subjects in order to remove any possible contamination due to carry-over effects (Poulton 1982), and workload was again manipulated within-subjects. Table 3 provides a schematic representation of the temporal availability of information provided within the four Fused conditions. The 'on2off8' Fused condition

replicated the temporal availability of location information provided within the UnFused display (Experiments 1 and 2). The 'on8off2' condition reversed the temporal cycle of the 'on2off8' condition. In doing so, the duration for which location information was unavailable within the display was reduced to two seconds, yet the frequency with which Fused information flashed on/off within each ten second cycle was held constant. The extent to which attentional factors affected performance within the current task were evaluated with respect to the 'on1off4' condition, during which location information was available for a total of two seconds (on two separate one second episodes) within the Fused display for every ten second cycle. The on1off4 condition thus provided participants with onscreen information for the same duration as the on2off8 condition, but reflected an on-/off- set frequency ratio of 2:1.

[Insert Table 3 about here]

These four conditions allow for selected critical comparisons to be made on the recall data. Firstly, each of the semi-permanent Fused conditions (on2off8, on8off2, on1off4) can be compared to the on10 condition, in which Fused information was permanently available onscreen, in order to assess the extent to which reducing the availability of Fused information improves retention. Secondly, if the relative importance of duration takes precedence, we would expect the on2off8 and on1off4 conditions (both of which have a total off duration of 8 seconds in every 10 second cycle) to yield better retention of location information than the on8off2 condition (which has a total off duration of 2 seconds in every 10 second cycle). Finally, if the

relative importance of frequency outweighs that of duration, we would expect the on1off4 condition (with an on-/off- set frequency of two per 10 second cycle) to yield better retention of location information than both the on2off8 and on8off2 conditions (each with an on-/off- set frequency of one per 10 second cycle).

5.1.3. Materials and procedure. The materials and procedure were identical to those employed during Experiment 2, with the exception that participants experienced six experimental trials, rather than twelve (three with one location, three with three locations). In addition, the retention interval was reduced to 1.5 minutes in order to verify the resilience of the effect with a shorter retention time that may be important in operational contexts.

5.2. Results

5.2.1. Location accuracy. A 4 (Prompt 1/2/3/4) x 2 (Locations 1/3) x 4 (Temporal Availability of Fused Information) ANOVA was computed with the first two factors manipulated within-subjects and the final factor manipulated between-subjects. A main effect was found for the availability of information, $F(3, 75) = 3.30$, $p < .05$, $MSE = 9.01$ (see Table 4), with Bonferroni corrected post hoc analyses indicating that only the on8off2 condition significantly improved location accuracy relative to the on10 condition ($p < .05$). The presence of a main effect of prompt, $F(1.76, 131.99) = 409.47$, $p < .001$, $MSE = 6.44$, indicated that participants' location estimations became more accurate over time. Although no main effect of locations was found, $F(1, 75) = 0.03$, $p > .05$, $MSE = 4.92$, simple main effects examining the locations x prompt interaction, $F(1.91, 143.28) = 133.73$, $p < .001$, $MSE = 10.15$, indicated that accuracy

decreased as the number of locations increased at prompts two, three and four (*ps*

<.01), but increased at prompt one (*p* <.001).

[Insert Table 4 about here]

5.2.2. Location retention. A 2 (Immediate/Delayed) x 2 (Locations 1/3) x 4

(Temporal Availability of Fused Information) ANOVA was computed upon the

immediate and delayed recall data with the first two factors manipulated within-

subjects and the final factor manipulated between-subjects. A reciprocal

transformation was required to correct for differences in variance between the two

fusion conditions. Accuracy of estimates decreased during the retention interval, F (1,

75) = 84.21, *p* <.001, *MSE* = 0.10, and as onscreen information became available for

longer periods of time, F (3, 75) = 5.76, *p* <.001 *MSE* = 0.14. Again, a retention time

x availability of information interaction was found, F (3, 75) = 3.36, *p* <.05, *MSE* =

0.10, (see Figure 4). Although simple main effects pointed to an effect of availability

of information at the final prompt (immediate), F (3, 75) = 5.40, *p* <.01, but not at

delayed recall, F (3, 75) = 1.76, *p* >.05, planned comparisons revealed that

participants in the on2off8 and on1off4 conditions exhibited significantly more

accurate delayed recollection when compared to the on10 condition (*ps* <.05). No

differences were observed in recall between the on8off2 versus on10, the on8off2

versus on2off8, or the on1off4 versus on2off8 comparisons (*ps* >.05).

[Insert Figure 4 about here]

5.3. Discussion

Reducing the availability of onscreen information within the Fused display not only increased the memorability of location information, but also improved participants' location accuracy during flight missions. Specifically, the on8off2 semi-permanent condition improved location accuracy during flight, and the on2off8 and on1off4 semi-permanent conditions improved memory after flight, relative to the permanent Fused condition.

Although not predicted, it is perhaps not surprising that the on8off2 condition improved location accuracy during flight missions when compared to the on10 condition. Mosier, Skitka, Heers, and Burdick (1997) pointed out that pilots tend to use automated cues as a heuristic replacement for information seeking, and tend to rely upon these cues despite conflict between expected and actual automation performance. Perhaps the semi-permanent nature of information provided within the on8off2 Fused condition minimized over-reliance on the onscreen location estimates (never 100% accurate), and promoted internal inference making (Glover 1989, McNamara et al. 1996). Provided that inference making was accurate, such a strategy may have allowed participants to formulate more accurate estimations than those provided within the external display. A possible reason why the on2off8 and on1off4 semi-permanent conditions (both of which removed onscreen information from eight seconds of every ten) did not also lead to improvement in location accuracy during flight may be due to the considerably larger demands placed upon working memory (Baddeley 1986). Importantly, however, no decrement in performance during flight

missions was witnessed in these conditions relative to the on10 condition, in which Fused information was permanently provided within the external display.

Support was found for our prediction that reducing the temporal availability of information provided within the external display would improve the encoding of fused information. Location recall was found to be superior in both of the semi-permanent Fused conditions that removed onscreen information for eight seconds of every ten second cycle (on2off8, on1off4), when compared to the Fused condition where onscreen information was permanently available within the interface (on10). However, an exception was that when information was removed for only two seconds of every ten second cycle (on8off2), recall measures did not differ to when information was continually available throughout each ten second cycle. This suggests that a threshold value for the unavailability of Fused information may exist in order to improve retention, even though there is not a significant difference between the on2off8 and on8off2 conditions.

The next issue concerns the possible explanation for improved recall for semi-permanent Fused information. The fact that the on1off4 condition did not improve retention relative to the on2off8 condition (despite a doubled on-/off- set frequency, with duration held constant) supports the proposition that attentional capture (Yantis 1993, Sutcliffe 1995, Yantis and Jonides 1996), at least within the on/off-set frequencies examined here, is unimportant. However, the improved recall observed in the on2off8 and on1off4 conditions (both of which remove information for eight seconds of every ten second cycle); relative to the on10 condition, strongly suggests that it is the duration with which Fused information is made temporarily unavailable that is responsible for improved recall. Hence it is the process of inference making (Palmiter et al. 1991, McNamara et al. 1996), and the use of memory when

information was unavailable during flight missions (Fu and Gray 2000, Gray and Fu 2004, Gray et al. 2006) that improved the encoding of fused information in the current task (Anderson and Milson 1989, Anderson and Schooler 1991, Schmidt and Bjork 1992, Duggan and Payne 2000).

Again, it is emphasised that the improved encoding of Fused information observed as a function of reducing the temporal availability of information provided within the external display did not lead to an associated decrement in location accuracy during flight performance. In addition, the lack of an interaction between location and temporal availability of Fused information during flight performance suggests that each of the Fused conditions was affected in much the same way by changes in workload.

6. General discussion

Preliminary evidence is provided supporting the concern outlined in the introduction that under certain circumstances, the provision of highly accessible information within a Fused interface may lead to impoverished encoding and problematic retention of visual-spatial information. Experiments 1 and 2 indicated that the provision of permanently available, integrated information in the Fused display improved location accuracy during flight missions, supporting much work conducted within the field of cognitive engineering (Woods 1991, Bennett and Flach 1992, Wickens and Carswell 1995, Lintern et al. 1999, Vicente 2002). However, the retention of location information derived from the Fused environment deteriorated disproportionately, when compared to the UnFused condition (in which onscreen information was not integrated and only provided for two seconds of every ten second

cycle). Experiment 3 demonstrated that memory for fused information within the current task could be improved by reducing operator reliance upon the interface as an external memory source (O'Regan 1992, Gray et al. 2006), and encouraging transfer-appropriate processing (Morris et al. 1979) such as inference making (Palmiter et al. 1991, McNamara et al. 1996) and the use of internal memory (Anderson and Milson 1989).

Essentially, this paper demonstrates that a sensitive balance exists between reducing an operator's cognitive workload by making the required information more accessible (Kirsh 2000), and ensuring that extraction of information is not made so effortless that information is promptly forgotten. The deployment of internal memory during information seeking reduces as information becomes more accessible within the interface (Ballard et al. 1995, Fu and Gray 2000, Gray and Fu 2004, Gray et al. 2006, Waldron et al. 2006), which can have negative consequences for the activation of memory traces in the future (Schmidt and Bjork 1992, Anderson, Fincham, and Douglas 1999). The current paper provides a topical, perhaps counter-intuitive example, whereby actually *reducing* the availability of Fused information provided within the external display improves subsequent performance.

Task performance criteria will dictate whether memory encoding is beneficial. Some may argue that efficacious encoding and retention of information provided within task environments such as the one chosen for the current study is not necessary. Such displays are designed so as to allow the operator instant access to the information needed, thus memory often becomes redundant. However, humans will always be required to monitor, supervise, adjust, and maintain augmented displays (see Bainbridge 1987) which, on occasion will fail. Indeed, Reising and Sanderson (2004) have highlighted the consequences of instrument failure within a display

influenced by Ecological Interface Design and stated that 'the more an arrangement of parts adds information beyond that in the parts alone – the more devastating the impact of a faulty sensor might be' (p.317).

Developing an internal representation of the information provided within the external display will benefit situations in which information previously presented, and no longer available onscreen, is to be unexpectedly recalled. Reinstating intentions and memory following task interruption can be difficult (Edwards and Gronlund 1998, Einstein, McDaniel, Williford, Pagan, and Dismukes 2003), and recent research has begun to examine methods by which task and interface design can support interruption tolerance (e.g. Oulasvirta and Saariluoma 2006). Designing the interface in order to actively facilitate the development of memory skills is likely to provide some resilience to the negative effects of interruption, and will undoubtedly complement an operator's overall situation awareness (see Banbury and Tremblay 2004 for a cognitive perspective of this concept).

However, it is anticipated that display manipulations designed to promote the development of a robust internal representation of the information presented externally will be easier in some situations than others. For example, memory for locations assessed in the current set of studies will have had semantic and relational properties with regards to landmarks situated within the terrain map (of which there were many). The mental organisation of such information has been shown to be influenced by the manner in which a map is learnt (Curiel and Radvansky 1998), and long-term working memory for visual representations of natural scenes is surprisingly robust and long-standing (Hollingwoth 2005). Whether reducing operator reliance upon an interface representing detailed physical information would have similar

effects to those observed in the current article is yet to be seen, but is likely to prove

more difficult (Vicente 1992).

It is fully acknowledged that the paramount function of any external display is to

provide operators with the information needed, when needed. Indeed, it would be

defeatist to provide the operator with the necessary information for the majority of the

task, only to remove critical information when it is required most. Therefore, much

research is required in order to develop effective methods and guidelines by which

active encoding of highly accessible information can be promoted, without

compromising the presentation of such information in a timely fashion. Adaptive task

allocation (Parasuraman, Mouloua, and Molloy 1996) may provide a means of

'refreshing' an operator's memory for fused information, and has previously been

used to improve an operator's mental picture of automated processes (Parasuraman

1993). As has been recognised in the automation literature (Parasuraman 2000), we

argue that the use of fusion is not necessarily an 'all-or-none' concept. Instead, it is

proposed that the use of fusion be adaptive to differing task demands and work in

harmony with what we already know about the human information processing system

(e.g. Wickens 1992).

Adaptively deploying fusion capabilities may well lead to improvements in

human performance when compared to the static use of fusion. This is often cited as

being the case in the automation literature (e.g. Hilburn, Jorna, Byrne, and

Parasuraman 1997), particularly when lower-order sensory and psychomotor

functions such as information acquisition are under investigation (Kaber, Wright,

Prinzel, and Clamann 2005). Lintern (1980) provides a good example of the benefits

of adaptively providing supplementary visual cues during a simulated aircraft landing

task. When compared to conditions in which visual cues were either not provided at

all, or were presented continuously during training, transfer of skill was found to be superior when cues were provided adaptively within the external display. According to Lintern (1980), participants relied too heavily upon extrinsic visual cues when provided continuously, and were in need of assistance when they were not provided at all. Although training is not the focus of the current article, it is envisaged that similar methods based upon evaluations of operator workload (e.g. Kaber et al. 2005, Gregoriades and Sutcliffe 2006) and sensitive to limited cognitive resources (Wickens 2002) may improve the design of a variety of fused environments.

A number of limitations have to be acknowledged with respect to the experiments reported in this paper. The balance between investigation of a topic within an applied context and within controlled laboratory conditions is often problematic to effect. Experiment 1 had the benefit of using highly skilled pilots, albeit only a few in number, using a high fidelity flight simulator whereas Experiments 2 and 3 utilised naive students as participants, using a low fidelity simulation. Whilst Experiment 1 presented a rich and realistic context with experienced pilots, it was not practically feasible to continue using this expensive resource in order to disentangle all the potential confounding factors in subsequent experiments. Consequently, Experiment 2 attempted to eliminate some of these variables, and replicate the results of Experiment 1. Although our student participants would not have developed the domain specific encoding structures of experienced pilots, we expected that they would have been familiar with information typically provided within standard maps. Also, the design of Experiment 3 was deliberately not intended to explore the possible contribution of representational equivalence (Larkin & Simon, 1987) between conditions, but rather, to pursue an important applied issue

of how to improve the retention of fused information, as configured in our task environment.

Our paradoxical assertion that memory for fused information may be improved by reducing the temporal availability of information provided within the interface is also somewhat limited to the scenario currently under investigation. In order to evaluate the generalisability of this finding, research is required in different settings. Indeed, it is expected that such a method will suit some scenarios yet not others. Where the scheduled removal of onscreen information is not appropriate, what is termed 'germane cognitive load' of a different nature may be necessary in order to improve the encoding and subsequent retention of visual-spatial information (see Paas and Kester 2006 for a review). It is anticipated, nevertheless, that the underlying principles discussed throughout the current paper extend to a variety of task domains, and are worthy of careful consideration during the design of fused environments of the future.

Acknowledgements

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Table 1

The Effect of Fusion and Workload on Location Accuracy (Experiment 1).

	Fused		UnFused	
Locations	Mean Error	SD	Mean Error	SD
1	2.48	2.85	2.57	0.80
2	1.33	0.60	6.95	3.21
3	3.12	2.27	4.99	2.02

Note. Values are given in nautical miles. Mean error is the difference between the actual and estimated

location.

Table 2

The Effect of Fusion and Workload on Location Accuracy (Experiment 2).

	Fused		UnFused	
Locations	Mean Error	SD	Mean Error	SD
1	5.82	3.61	5.27	3.30
3	5.87	2.93	7.31	3.33

Note. Values are given in nautical miles. Mean error is the difference between the actual and estimated location.

Table 3

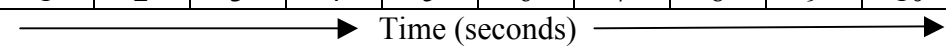*Schematic representation of the temporal availability of fused information in*

Experiment 3.

Condition	On-/off-set period									
on10	on									
on2off8	on		off							
on8off2	off		on							
on1off4	on		off			on		off		
	1	2	3	4	5	6	7	8	9	10
	→ Time (seconds) →									

Table 4

The Effect of Information Availability on Location Accuracy (Experiment 3).

Information Availability	Mean Error	SD
on10	6.16	4.04
on2off8	5.56	3.64
on8off2	5.17	3.30
on1off4	5.34	3.97

Note. Values are given in nautical miles. Mean Error is the difference between the actual and estimated location.

FIGURE CAPTIONS

Figure 1: Representation of fused (a) and unfused (b) displays.

Note. Screenshots taken from a simulation of the IFT with three locations, omitting maps used. The intersections of unfused

spokes furthest from both aircraft represent the best estimates of location.

Figure 2: Effect of fusion and retention interval on location accuracy (Experiment 1).

Note. Mean error is the difference between actual and estimated location. Error bars represent ±1 standard error.

Figure 3: Effect of fusion and retention interval on location accuracy (Experiment 2).

Note. Mean error is the difference between actual and estimated location. Error bars represent ±1 standard error.

Figure 4: Effect of the availability of onscreen information and retention interval on

location accuracy (Experiment 3).

Note. Mean error is the difference between actual and estimated location. Error bars represent ±1 standard error.

Figure 1
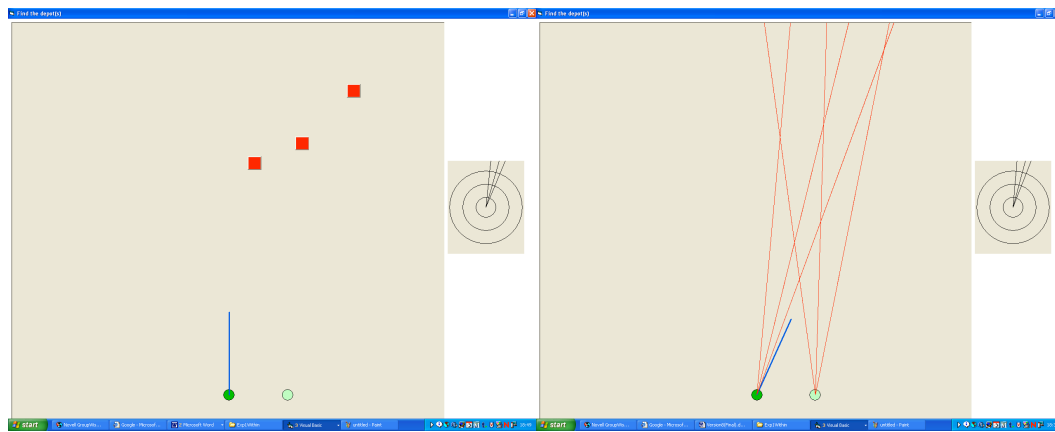
(a) Fused   (b) UnFused
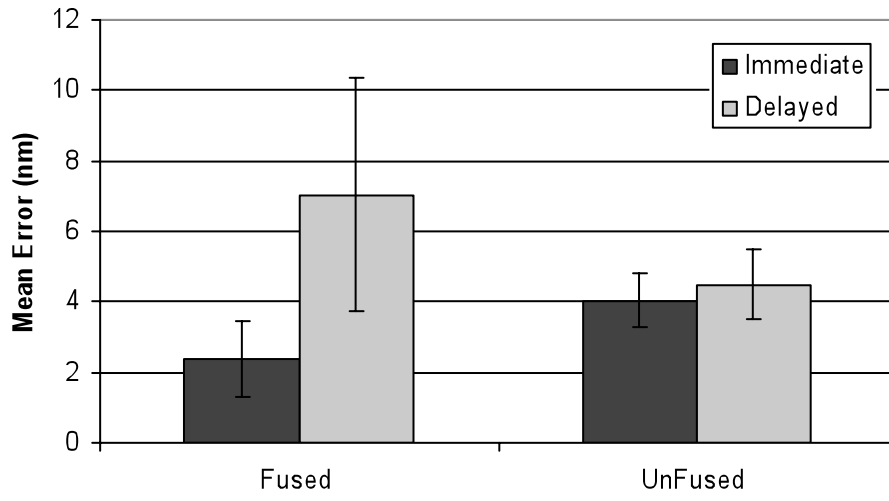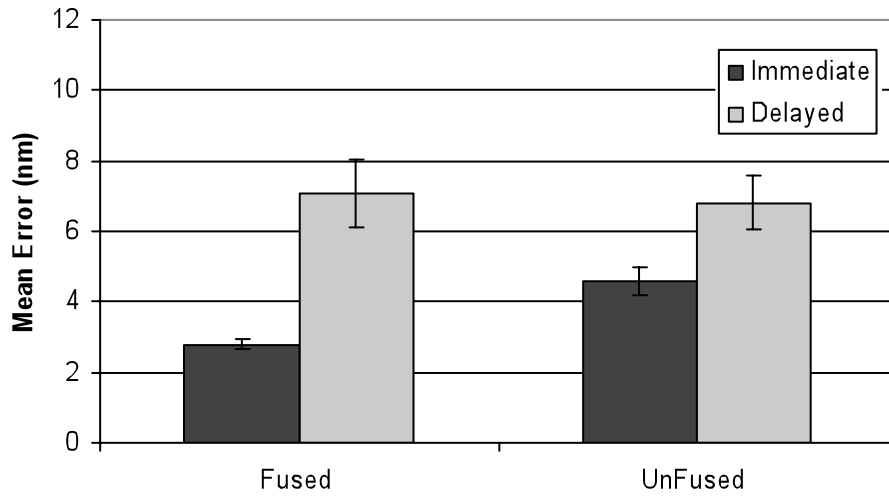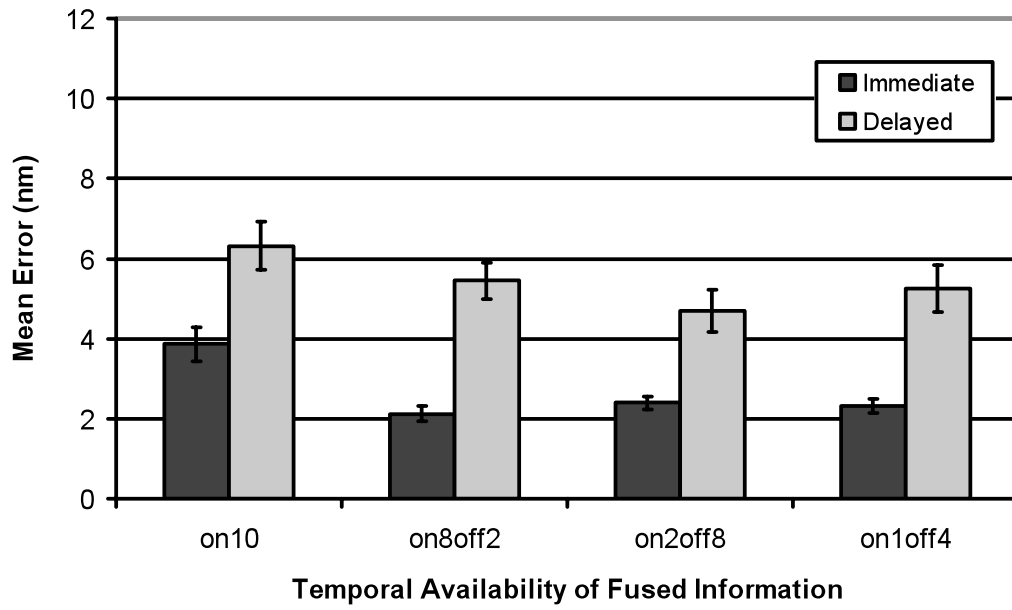
Figure 2

Figure 3

Figure 4

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