Aviation Human Factors Division
Institute of Aviation

University of Illinois
at Urbana-Champaign
1 Airport Road
Savoy, Illinois 61874

Display Size Contamination of Attentional and Spatial Tasks: An Evaluation of Display Minification and Axis Compression

Emily K. Muthard & Christopher D. Wickens

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ABSTRACT

Four experiments were conducted to evaluate the influence of display size on attentional and spatial tasks. In Experiments 1 and 2, display size was manipulated by enlarging the physical size of a top-down 2D integrated hazard display. Pilots were asked to monitor the airspace for changes in the trajectory or altitude of traffic aircraft or weather systems. In Experiment 1, pilots were also asked to periodically search the airspace for key hazards. In Experiment 2, this probe task was removed to examine surveillance unconfounded by search and display clutter was added. In both experiments, pilots were found to consistently adjust scanning patterns to account for an enlargement of the display area, and thus the area to be monitored. While change detection performance was worsened for events occurring near the display periphery, this effect was not amplified when the display was enlarged. Search was also unaffected by display size. For experiment 2, clutter reduced detection performance in the smallest display, where display density was amplified because of the minification. In Experiment 3, pilots were asked to complete a compensatory tracking task with a simplified flight control display. Display size was manipulated by changing the physical size of a 2D display and through axis compression in a 3D display. In both cases, pilots were found to exhibit higher tracking error and lowered control activity when display size was reduced, and this effect was amplified for axis compression. This performance reduction was hypothesized to have resulted both from the lowered resolution of the smaller display, which provided less information about small deviations than its larger counterpart, and from reduced urgency, as pilots perceived the smaller *displayed* errors as less severe path deviations. Finally, in Experiment 4, pilots were asked to select one of two flight paths that traversed through a hazardous airspace, as well as rate the safety of the flight paths. The size of the integrated hazard display was again manipulated by reducing the physical size of the 2D display or through axis compression of the 3D display. Results indicated that pilots were more likely to overestimate the span between their own aircraft and environmental hazards when this distance was portrayed on a large display, regardless of the means through which size was manipulated. When display size was manipulated through axis compression, this overestimation translated into an unsafe route choice. Analyses suggest that display enlargement can be made without imposing detrimental effort costs to attentional tasks, but spatial estimates become biased by display scale and influence resultant flight control and route selection tasks.

CHAPTER 1: INTRODUCTION

Recent technological advances have allowed for a growing number of displays to be designed for the modern flight deck. Unfortunately, real estate within the cockpit is limited, thus potentially causing designers to minify the displays to ensure that each will fit within the cramped space. Such pressures, however, represent only half of the variations of display size that are occurring in display design. Pressures to create large-scale displays that synthetically represent the world seen from the cockpit, such as synthetic vision displays (e.g., Prinzel, Comstock, Glaab, Kramer, & Arthur, 2004; Schnell, Kwon, Merchant, & Etherington, 2004), also influence designers to alter display sizes. New features are also being proposed for the cockpit display of traffic information (CDTI), which will allow pilots to manually zoom in on display regions, thus altering the geometric field of view of the display and the scale of the information presented. The impact of making such size changes on the pilot performance in a variety of tasks has not been widely researched. Thus, the proposed experiments seek to investigate the impact of display size on surveillance, distance estimation, flight control, and decision making.

The following sections will explore the extent to which manipulations in the size of a multi-task display can influence the four classes of tasks mentioned above. The investigation will first focus briefly on an introduction of the multi-task integrated hazard display and will then turn to a description of the four manners through which size can be manipulated. The tasks of surveillance, distance estimation, flight control, and decision making will be examined in the context of changes to display size. The review will conclude with a summary of the presented findings and predictions for present experiments.

1.1 Integrated Hazard Display

The advances that have been made in display technology have allowed for the presentation of multiple information databases in a single display panel, thus allowing for the support of several tasks simultaneously. One such display is the integrated hazard display (see Kroft & Wickens, 2003; Muthard & Wickens, 2002; Ververs, Dorneich, Good, & Downs, 2002), which presents several classes of hazards overlaid in a single panel format. These hazards typically include traffic aircraft, weather systems, and terrain or other land features, such as high towers or structures, of which the pilot must be aware when traveling through the airspace. Figure 1.1.1 depicts one example of an integrated hazard display.

Including several sources of information in this form of integrated display assists in supporting pilot's situation awareness (Endsley, 1995) by presenting all relevant information in one location and reducing scanning demands. The integrated display layout can also assist the pilot in creating an integrated mental picture of the airspace (Kroft & Wickens, 2003), which is necessary for predicting the future locations of environmental threats and for assessing the safety and feasibility of flight routes. While the display is effective in reducing scanning demands and assisting in situation awareness, the optimal size of this display remains an important area of investigation because of the tradeoff in perceptual and cognitive factors that co-vary with display size, as discussed below.

1.2 Manipulating Display Size

Any change in the size of a display results in a manipulation to the display *scale.* Generally this scale is represented as a ratio of display units to world units (e.g., 1 cm = 5000 m). Display units are typically represented as pixels, centimeters, or degrees of visual angle. These display units, however, are representative of more meaningful world units, which can be measured in meters, nautical miles, or degrees of heading. This ratio of display units to world units will differ with any variation in display size and can be manipulated in four ways, as shown in Figure 1.2.1.

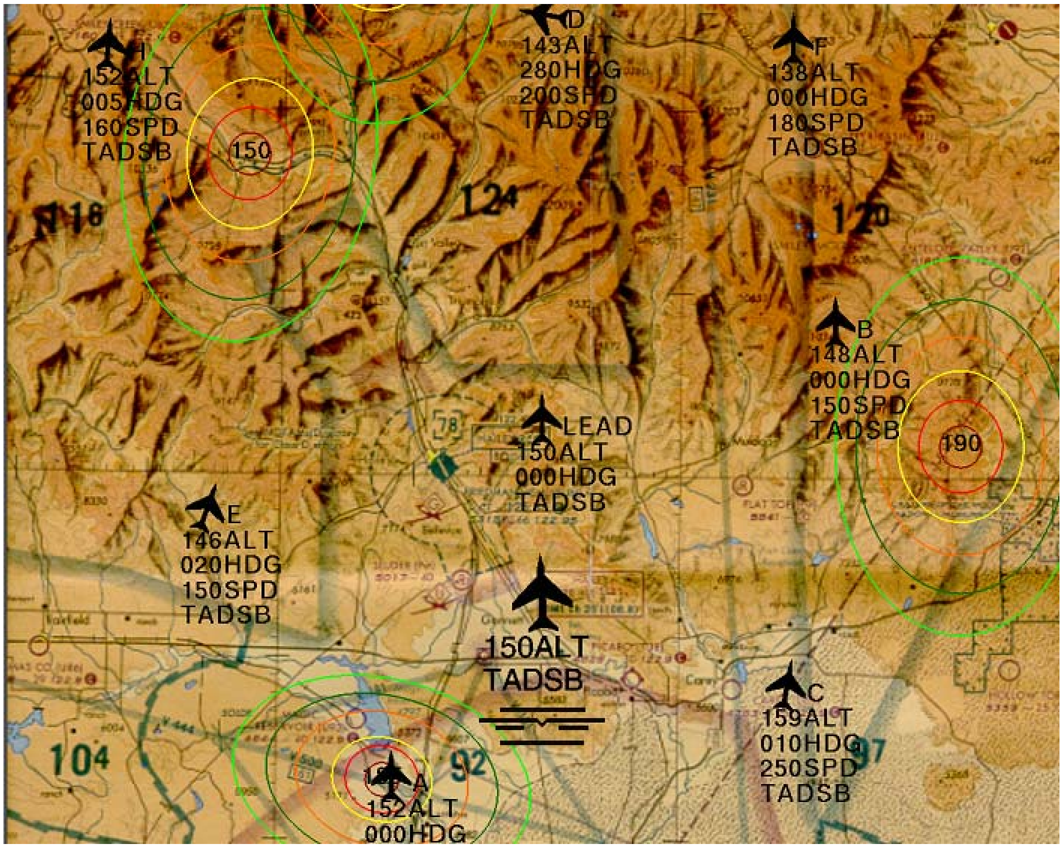


Figure 1.1.1 . Integrated hazard display depicting air traffic, weather systems, and terrain (topographical map). Ownship is the larger aircraft icon located in the bottom center of the display.

Manipulating the physical size of the display by enlarging or reducing the overall dimensions of the display (see Figure 1.2.1a) represents the most basic way to produce changes in the display units to world units ratio. Variations in the geometric field of view, which results when the view of the airspace is zoomed in or out without changing the size of the display itself, will also produce differences in the display units to world units ratio. Thus, displays with a large geometric field of view (see Figure 1.2.1b) portray a larger area of the airspace, but will do so in a smaller scale than a display with a zoomed in perspective. When the dimensions of the display and the information in the display is held constant, changing the distance from which the display is viewed will result in manipulations to the visual angle (see Figure 1.2.1c) that the display encompasses and the size of the display. While these three approaches are can be used to produce display size changes in both two-dimensional and three-dimensional displays, the final approach is exclusively inherent to three-dimensional displays.

When information is presented in a three-dimensional display, representation of that three-dimensional world on a two-dimensional display plane requires that the axis parallel to the line of sight become compressed (Boeckman & Wickens, 2001). As a result, the world distances along this axis are presented with smaller display distances resulting in a unique form of display minification (Boeckman & Wickens, 2001; Boyer & Wickens, 1994). The extent of display minification decreases as the display plane is rotated away from the line of sight and is entirely reduced when the plane is fully orthogonal to the line of sight axis (Barfield, Hendrix, & Bjorneseth, 1995).

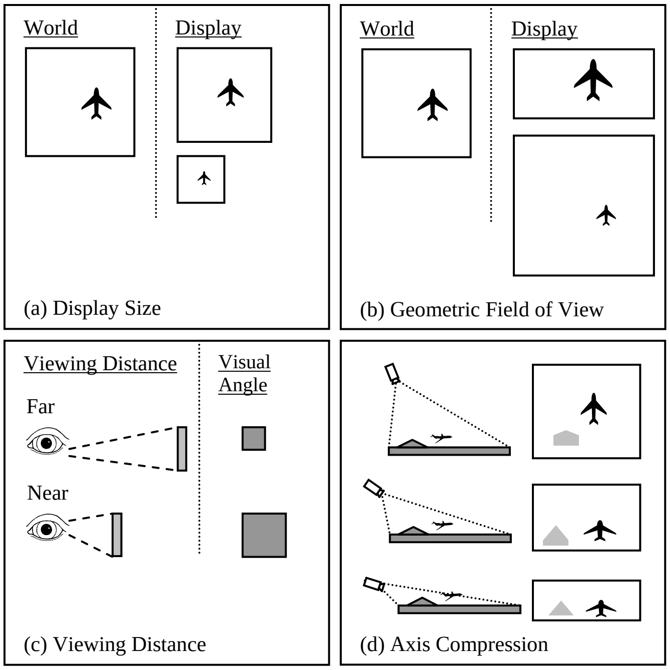


Figure 1.2.1. Differences in display size due to (a) physical size, (b) geometric field of view, (c) viewing distance, and (d) the compression of an axis in three-dimensional displays. In (d) the compressed axis (here the depth axis) is represented by fewer display units and a smaller visual angle than the uncompressed (here the lateral axis) axis.

Thus, display size can be uniquely manipulated by altering the physical display dimensions, changing the display field of view, increasing or decreasing the distance at which the display is viewed, and by presenting information in a three-dimensional display. While these methods can be used to manipulate display size, the objects or relationships of objects depicted in the display are not affected. It may be the case, however, that they impact the manner in which the objects are monitored and the *perceptions* of the relationships of the objects.

The first pair of experiments in the present study will investigate how manipulations to the physical size of a two-dimensional display (Figure 1.2.1a) can influence the attention-based tasks of surveillance and reading. The latter experiments will examine how manipulating display size, either by changing the physical size of a two-dimensional display or through axis compression along the line of sight in a three-dimensional display, affects spatial judgment and resultant flight control and flight route selection. The following provides a description of four aviation tasks, namely surveillance, distance estimation, tracking, and judgment, and a review of how these tasks might be expected change with manipulations to the size of a display.

1.3 Display Surveillance and Reading

Change Detection. When traveling through the airspace, a pilot must monitor weather and traffic threats for changes in the lateral and vertical behavior of these hazards. This task can be mapped to a widely researched phenomenon termed "change blindness" (Carpenter, 2001; Rensink, 2002; Simons, 2000), which refers to the difficulty that individuals have in detecting changes to a visual scene that occur outside of the focus of attention (Levin & Simons, 1997;

Rensink, O'Regan, & Clark, 1997). Change blindness has also been found to inhibit pilots from detecting the important changes that occur to the altitude or heading of traffic aircraft and weather systems (Podczerwinski, Wickens, & Alexander, 2001; Muthard & Wickens, 2002, 2004). Thus, the change detection task serves as a useful measure for assessing the effects of physical display size on surveillance.

Display Size Effects on Surveillance. A growing body of research has shown that the ability to detect a change is dependent on the location of event with respect to focused attention (Beck et al., 2001; Rensink et al., 1997; Rensink, 2000). Thus, change detection performance degrades with increasing distance from the center of focused attention (McConkie & Loschky, 2000; Muthard & Wickens, 2004; Podczerwinski et al., 2001; Pringle et al., 2001). These peripheral events can be difficult to detect for two reasons, namely reduced expectation and effort.

In aviation displays, the representation of the pilot's own aircraft generally serves as the focus of attention (Muthard & Wickens, 2004). Thus, changes that that occur further from ownship, while distant from the focus of attention, also generally pose less of an immediate risk to the pilot's flight safety and are thus less important. While event relevance and expectancy influences detection, research has indicated that even when controlling for the relevance of an event, change detection is slowed by approximately one second for each six degrees of visual angle of eccentricity (Podczerwinski et al., 2001). While the magnitude of the effect is small, the finding suggests that an additional mechanism is operating to influence surveillance, namely effort.

As information is displaced from the central focus of attention, the effort that must be invested to access that information also increases. This idea has been described by Wickens (1992) in an information access effort model, which posits that the amount of resources invested to acquire information increases nonlinearly with eye movements and head movements of increasing magnitude. While eye movements can be used for accessing most of the display, information at displacements greater than twenty degrees of visual angle typically require head movements to access (Bahill, Adler, & Stark, 1975), which requires a larger effort investment than eye movements. To the extent that the amount of effort needed to access information becomes too great, the pilot might resort to monitoring only the central portion of the display. This phenomenon has been termed the "edge effect" (Baker, Morris, & Steedman, 1960; Enoch, 1959; Schoonard, Gould, & Miller, 1973). Because display enlargement causes a greater proportion of the display to be transferred to the periphery, the edge effect might be amplified the physical size of a display is increased. If the pilot is able to successfully allocate attention to the enlarged peripheral display areas, no decrement in surveillance performance would be found. These two approaches serve as the basis for the hypothesized effects of size on surveillance.

Two Strategies: Effort Conservation and Strategic Compensation. Pilots may attempt to employ two surveillance strategies to account for the enlargement of an integrated hazard display (see Figure 1.3.1a). The presented review of research on effort and the edge effect lends support to the *effort conservation* strategy (see Figure 1.3.1b). Under this strategy, the effort needed to monitor a large display toward its periphery is too difficult to maintain over an extended period of time. Consequently, the pilot neglects the display periphery and allocates attention to the central portion of the display. The degree to which performance suffers as a result of the display enlargement is predicted to be directly proportional to the ratio of display sizes. Providing evidence of this approach, Enoch (1959), in an evaluation of search with aerial maps, indicated that display enlargement resulted in shorter fixations and longer saccades. Enoch argued that fixation length was reduced because fixations to peripheral display regions were difficult to maintain and because additional time was needed to make longer saccades to these regions. Enoch also concluded that the concentration of fixations was located at the center of the aerial maps, particularly with larger display sizes. Collectively, these results point to the heightened role of effort for search and surveillance with larger display sizes.

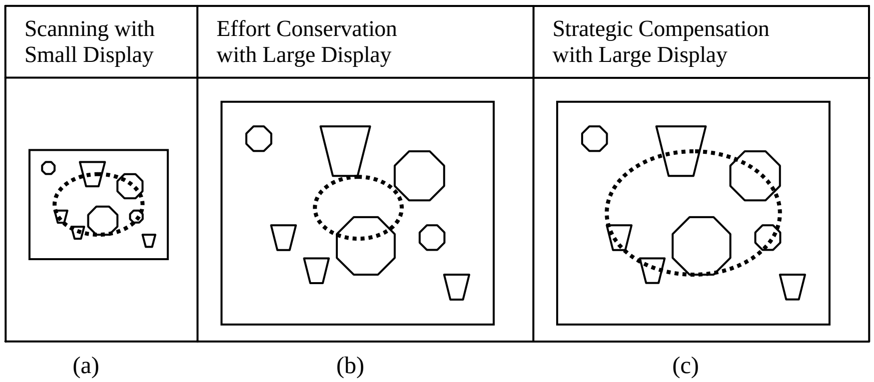


Figure 1.3.1. (a) Scanning allocation with small display, exhibiting edge effect. (b) Scanning under effort conservation hypothesis, depicting equal scanning pattern to that in the small display. (c) Scanning under strategic compensation hypothesis, depicting adaptive zoom lens.

The second strategy that pilots may exhibit is one of *strategic compensation* (Figure 1.3.1c). Under this approach, the pilot recognizes the need to adapt and enlarge scanning patterns in response to display size changes. Thus, the observer will expend the extra effort that is needed to survey the larger display. If this strategy is fully implemented and effort conservation is ignored, the pilot should not exhibit surveillance performance differences across display sizes. No known research has been conducted that provides evidence of the strategic compensation approach.

Figure 1.3.2 presents the predictions of effort conservation and strategic compensation hypotheses as a function of physical display size. While the discussion to this point has presented two extreme approaches to surveillance, observers may also exhibit a strategy that combines the two approaches (see Figure 1.3.2). This “middle of the road” approach will most likely be employed when the individual attempts to increase the size of the search field in accordance with the strategic compensation approach, but is unable to maintain the field size when the attention allocation effort becomes too great. This threshold can be reached if concurrent tasks become too numerous or difficult (Recarte & Nunes, 2002), or if the surveillance task becomes too effortful.

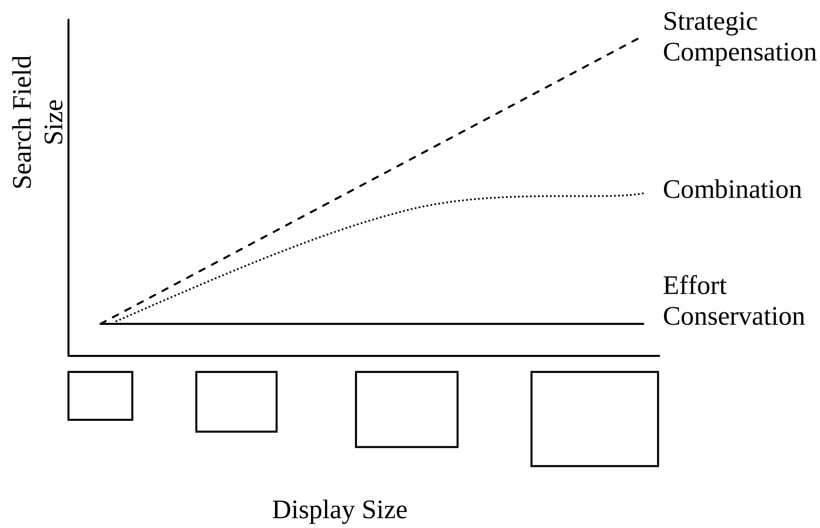


Figure 1.3.2. Hypothesized variations of search field size. If a strategic compensation strategy is employed, participants will enlarge search field size with display enlargements. Under effort conservation, however, the participant will not change search field size with enlargements, due to constraints on deployed effort. Under a combination approach, the participant may increase the search field size (strategic compensation) with display enlargements until the effort becomes too great, choosing upon that point to maintain the only marginally enlarged search area (effort conservation).

Display Clutter. Display clutter has been most commonly classified in two forms, namely local and global density clutter (Tullis, 1988). While global clutter refers to the total number of items in a display (Wickens, Vincow, Schopper, & Lincoln, 1997) or the density of the display (Currasco, Evert, Chang, & Katz, 1995; Carrasco & Frieder, 1996), it can also be measured as a function of the texture of edge density of the display (Rotman, Tidhar, & Kowalczyk, 1994). Conversely, local clutter refers to the amount of information surrounding a target display area (Wickens et al., 1997) and can be measured by assessing the edge distribution within and around the local environment of a target (Rotman et al., 1994) or by measuring the distance between the target element and nearby distracters (Intriligator & Cavanagh, 2001; Tripathy & Cavanagh, 2002).

Research examining the impact of clutter or display density on visual attention and surveillance has concluded that irrelevant information located within a scan path will increase information access effort (Schons & Wickens, 1993), thus inhibiting performance in locating, attending to, or monitoring display elements (Sanders & Houtmans, 1985). In fact, the mere presence of extraneous information located in the path of a scan (Wickens & Andre, 1990) or within close proximity to a target (Intriligator & Cavanagh, 2001; Tripathy & Cavanagh, 2002; Tullis, 1988) can inhibit focused attention to a target display element and visual scanning.

The performance decrement associated with display clutter has been attributed to both lateral masking and inhibition (Carrasco et al., 1995; Carrasco & Frieder, 1996; Carrasco & Yeshurun, 1998) and to limits in attentional resolution (Intriligator & Cavanagh, 2001; Tripathy & Cavanagh, 2002). Lateral masking occurs when the simultaneous and proximal presentation of distracter stimuli with a target stimulus must be processed by the same or neighboring receptive fields (Breitmeyer, 1984), thus inhibiting target discriminability. Attentional resolution limits, which are much coarser than that of spatial vision (Intriligator & Cavanagh, 2001), can also hinder the allocation of focused attention to densely positioned display elements. Specifically, elements that are positioned more closely to the target than the resolution of attentional selection will lead to the perception of multiple elements, thus reducing an observer's ability to focus on the target (Tripathy & Cavanagh, 2002). Tripathy & Cavanagh (2002) have defined the point at which the separation between a target element and distracters becomes too minimal and begins hindering target identification as the *extent of spatial interaction.* This parameter has been identified as ranging from 3.26 degrees for the periphery (Tripathy & Cavanagh, 2002) to 0.05 degrees directly at the fovea (Intriligator & Cavanagh, 2001).

While clutter alone can inhibit search and surveillance tasks, reducing a display's overall physical size, which in turn amplifies display density, can serve to intensify these predicted clutter effects. Consequently, information within presented in a small display format, particularly when that display is cluttered, will likely be located within the extent of spatial interaction. As a result, an observer will experience more difficulty in foveating only the target. While minification would reduce the magnitude of saccades that must be made to survey the display, since elements would be more closely spaced (Drury & Clement, 1978; Teichner & Mocharnuk, 1979), the resulting impact on performance and effort would likely be minimal.

Thus, display size can influence surveillance by increasing the amount of effort that is needed to monitor an enlarged display or by increasing the local density of a minified display. Manipulations of display size can also influence the ease with which pertinent information can be read.

Reading and Symbol Interpretation. Though the surveillance task is based on the allocation of attention to a region of space, the legibility of information that pertains to display elements that are being surveyed can also influence the monitoring task. In surveillance, this textual information must be read because the text itself may change, indicating a change in aircraft altitude or heading, or because an operator may need to use textual information to avoid confusion between objects.

The legibility of a symbol, letter, or word can be affected by the physical size of the text. In general, reading degrades with small text, particularly when characters subtend less than 0.1 degrees of visual angle (Gould & Grischowsky, 1986). These standards, however, are based on studies examining normal text reading rather than aviation display reading. In the former, contextual and sequential constraints of language can ease the burden caused by poor text legibility. When using aviation displays, however, such context may be absent and confusion between altitudes (flight levels) can have disastrous consequences. For example, a pilot who is traveling at 14,000 feet and perceives a traffic aircraft's data tag that reads 130 (13,000 ft) as 180 (18,000 ft), would unknowingly be in conflict with that aircraft. Corresponding confusions between geometric symbols (e.g., ○ vs. □) also abound as the sizes of the symbols, and thus the details that differentiate those symbols, are reduced. Thus, size standards for electronic displays are more conservative, indicating that primary text and symbols should not subtend less than 0.6 degrees of visual angle, while secondary data and legends should subtend no less than 0.3 degrees (Society of Automotive Engineers, 1985). While legibility can suffer with smaller text sizes, reading speeds can benefit because more text can be read with a single fixation (Snyder & Maddox, 1978).

Larger text sizes are generally used to improve text and symbol legibility. Larger text sizes not only allow for detailed information of the symbol or character to be viewed, but also result in larger spaces between the letters of the text (Wickelgren, 1979) allowing the features of the letters to become even more apparent (Wickens, Gordon, & Liu, 1998). The tasks of hazard awareness, route planning, and accurate flight control depend upon the pilot's ability to accurately perceive the detailed aspects of each symbol, and presenting the symbols in a larger size can assist in each of these tasks. Nevertheless, when larger text sizes are used, more fixations are needed to access the text (Gould & Grischkowsky, 1986; Smith, 1979). However, aviation displays portray only sparse textual information and this information can usually be accessed with a single fixation. Thus, this concern is reduced within the present context. Therefore, display enlargement can assist in reading textual and symbolic information in an integrated hazard display without an expected cost to scanning or information acquisition.

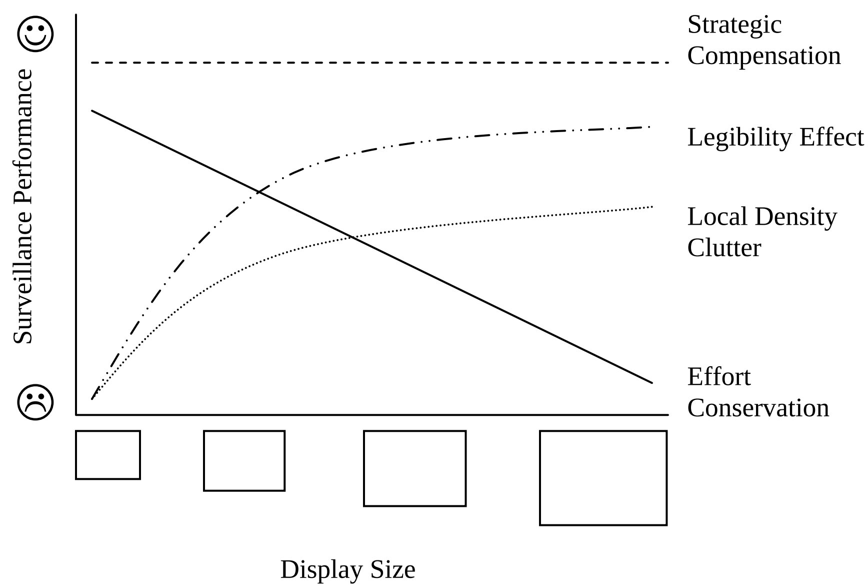


Figure 1.3.3. Predicted surveillance performance effects with display enlargement. Under the strategic compensation hypothesis, performance should not vary across size. Text and symbol legibility will hinder surveillance with the most minified displays, as will local density clutter. Both of these effects are assumed to be nonlinear, as they will not disrupt performance above a minimum value. The effort conservation hypothesis posits that surveillance will degrade linearly with display enlargements, as the extra effort needed to scan the greater display area will not be deployed.

Surveillance and Reading Summary. Monitoring the airspace for events with the use of a cluttered integrated hazard display can be a challenging task that pilots struggle to carry out effectively (Muthard & Wickens, 2002, 2004; Podczerwinski et al., 2001). Figure 1.3.3 provides a graphical summary of each of the predicted effects of surveillance strategy, reading performance, and local clutter density on surveillance as a function of display size. Specifically, text and symbol legibility and local density clutter are expected to improve nonlinearly with display enlargements. Surveillance performance changes in response to display enlargements will differ based on the pilot's chosen strategy. To the extent that the pilot conserves effort in scanning, an enlargement to the display size and the resultant displacement of information from the center of the display will impede surveillance. Conversely, strategic compensation for display enlargements can sustain performance across display sizes. Thus, performance changes that occur with display size manipulations depend on the pilot's scanning strategy in managing the enlarged display. Strategy also affects the pilot's performance in the remaining tasks that must be carried out during flight, namely assessing distance in flight control and risk assessment.

1.4 Distance Estimation

During flight, estimates of distance are used to determine the distance to an impending hazard, to maintain a determined separation from another aircraft, or to estimate an aircraft's deviation from its intended flight plan. For the task of flight control, this deviation estimate is used to determine the *urgency* with which path deviations should be corrected. For flight planning, the estimate is used to assess the risk of a flight path and subsequently in flight plan selection. Sometimes distance can be used as a surrogate to estimate time, which may be the function variable of greatest importance (e.g., time-to-contact). Figure 1.4.1 depicts the manner in which distance estimates are used as an initial step in both flight route decision making and tracking.

A true computational estimate of distance involves converting a display distance (measured in centimeters or pixels) to a world distance (measured in meters or miles), by dividing (explicitly or implicitly) the display distance by the map scale. Individuals have also been found to use a "laying off" strategy to estimate the length, thus forming a mental image of laying the scale upon the distance to be judged (Hartley, 1977). Under each of these approaches to distance estimation, the size of the display (or the magnitude of the ratio of display to world units) should not impact distance estimation performance, as each accounts for the scale of the display in the computation. While these operations promise to result in accurate distance judgments, the processes also require a great deal of cognitive effort to be performed precisely. When mental resources or time are limited, when several distance estimates must be made quickly, or when distance estimates must be used in the calculation of time-to-contact, these computational processes can be abandoned for a less time-consuming shortcut. Under a more simplistic approach, a pilot may use display distance alone as a substitute for world distance. While this strategy can work in the majority of instances, the approach might result in *size contamination*, in which the size of the display produces a difference in the estimation of world distances.

Size Contamination. Size contamination refers to the biasing influence of the ratio of display units to world units on estimates of world distance. Size contamination results when changes to the size of the display produce differences in the estimation of world distance, even though the world distance remains constant across display scales. Thus, a pilot estimating the distance between his own aircraft and an impending hazard may judge the distance as larger when it is portrayed on a large display. When this same distance is portrayed on a smaller display, the pilot may correspondingly judge this distance as smaller.

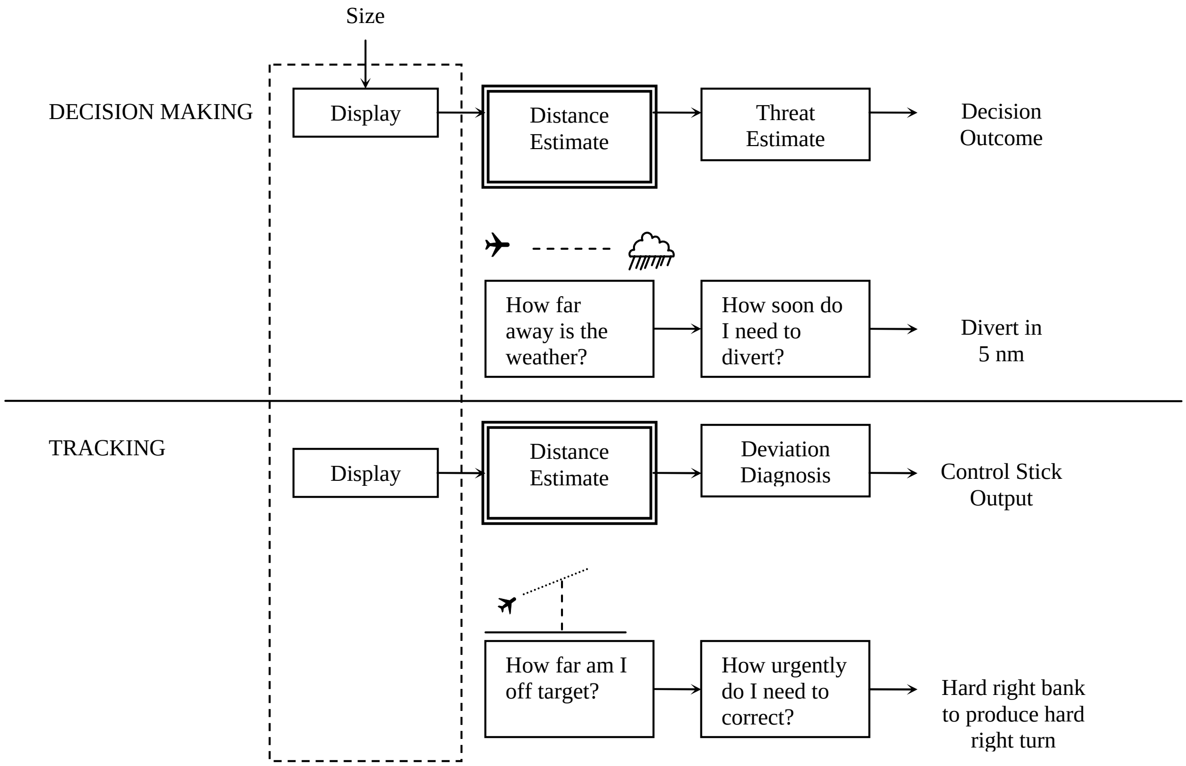


Figure 1.4.1. The role of distance estimation in decision making and tracking. In decision making, distance is estimated from an upcoming hazard and estimate is used as an assessment of risk. In tracking, distance estimate is based on the length between the intended flight path and the pilot's actual position, and thus estimate determines urgency with which deviations are corrected.

Size contamination is most likely to result when precise computational processes cannot be used to judge distance, particularly when time is limited or cognitive load is high. Whereas world distance information can only be accessed with these taxing processes, display distance information is *accessible* (Kahneman, 2003) and able to perceived quickly and effortlessly with a simple glance to the display. This process can be mapped onto Kahneman's (2003) two stage model, the initial stage of which is grounded in automatic perceptual processes (Kahneman & Tversky, 1983), while the latter is followed by a deliberate, resource-intensive stage that modifies these initial perceptions. Because the latter stage is dependent on sufficient time and resources, it can become negligent when an individual is performing several tasks concurrently, when time is constrained, or when the task is highly difficult (Kahneman, 2003; Kahneman & Frederick, 2002). As a result, information generated from the perceptually-driven first stage of the system may given more importance than is optimal. Translating this into the distance estimation task of interest here, the display distance will be automatically perceived in the initial stage of the process because of its ease of accessibility. In the latter stage, display scale and display distance would be computationally combined to produce an estimate of world distance. To the extent that resource or time constraints exist, however, the influence of stage two may be attenuated and the individual might rely more heavily on the display distance information obtained during stage one, allowing for display size to contaminate this estimate.

Research that has examined size contamination of distance estimates when size was changed by altering the scale of a two-dimensional display has not been conclusive. For example, the physical size of a display has not been found to affect terrain position judgments when using a display that synthetically represents to the three-dimensional view from the cockpit (Wickens, Alexander, & Hardy, 2003; Prinzel, Kramer, Comstock, Bailey, Hughes, & Russell, 2002). However, research examining the influence of physical display size on estimates of length has reported conflicting findings. In these studies, judgments of vertical and horizontal length exhibited estimates consistent with the vertical-horizontal illusion, for which observers consistently judge vertical lines as longer than horizontal lines, even when they are equal in length. Chapanis & Mankin (1967) evaluated this illusion for real world objects that varied in physical size, while viewing distance was manipulated so that retinal size (visual angle) was equal for all objects. Consistent with the predictions of the vertical-horizontal illusion, observers overestimated the height of most of the objects. Importantly, the degree of overestimation was greater for larger objects than for small, suggesting that scale may affect judgments of length. These findings were replicated by both Dixon and Proffitt (2002) and Yang, Dixon, and Proffitt (1999).

While this latter group of studies suggests a consistent and robust effect of size on judgments of distance, caution should taken in generalizing these findings to the present approach of physical size manipulation. In the discussed studies, the physical sizes of objects were varied in a manner consistent with our approach, but display viewing distance was simultaneously manipulated. To the extent that display units were measured in degrees of visual angle, the ratio of display units to world units remained consistent across the different display sizes. Thus, some effect of size was exhibited, but this effect is constrained to instances where the objects were physically sized differently but were equal in size when measured as visual angle.

While the literature on the effects of physical size in two dimensional displays is sparse, there is an extensive body of research that has demonstrated that distance estimates made with three-dimensional displays are biased by *axis compression* (Boeckman & Wickens, 2001; Hendrix & Barfield, 1994; McGreevy & Ellis, 1986; Yeh & Silverstein, 1992). One of the most prevalent studies examining position estimation biases in three-dimensional display was conducted by McGreevy and Ellis (1986). In this study, participants were asked to judge the elevation and azimuth angles of target cubes with respect to a reference cube, as displayed on a three-dimensional display. McGreevy and Ellis's (1986) results indicated that estimates were underestimated as the vector between the cubes became parallel to the line of sight. In subsequent studies, researchers (Boeckman & Wickens, 2001; Hendrix & Barfield, 1994; Yeh & Silverstein, 1992) conducted similar studies, replicating the findings of McGreevy and Ellis (1986) and providing additional support for the biasing effects of axis compression.

A subset of relevant research examining axis compression has emerged from comparisons of two-dimensional coplanar and three-dimensional displays. The coplanar display depicts a two panel representation of the airspace in which all three spatial axes of flight are fully expanded. By comparing performance of the coplanar display with that of the three-dimensional display, distance estimation performance with expanded and compressed axes is compared, respectively. To make this contrast, Wickens, Liang, Prevett, and Olmos (1996) examined position estimation performance with a two-dimensional coplanar and an integrated three-dimensional display. Their research indicated that the two-dimensional display facilitated more accurate vertical judgments, while judgments with the three-dimensional display were underestimated. The researchers attributed the performance difference to the compression of the vertical axis with the three-dimensional display. Several other researchers have found similar advantages for the uncompressed, coplanar display (Jasek, Pioch, & Zelter, 1995; Merwin & Wickens, 1996; O'Brien & Wickens, 1997; Wickens & Prevett, 1995).

Summary. Collectively, there is substantial evidence to suggest that participants' estimates are biased by the manner in which a distance is presented. Whether the display units to world units ratio is varied by manipulating the physical size of the display or through the compression of an axis in a three-dimensional representation, individuals employ a heuristic in which display units are used more heavily than is optimal to estimate world units. Though this finding is widely documented, and appears to be more robust for three-dimensional axis compression than for two-dimensional physical display size, it is unclear how these biases will be manifest in flight control and decision making tasks, both of which are important resultants of distance estimation.

1.5 Tracking and Flight Control

Tracking can be described as a processing involving a continuous set of discrete distance (error deviation) judgments followed by a control input, if the deviation is judged as significant enough to warrant correction (Wickens, 1977) (see Figure 1.4.1). The previous section detailed the conditions under which individuals use heuristics for estimating distance. The present section presents three models of how size can affect the task of tracking, the last of which will reflect the display distance bias described previously.

Normative Model. The normative model describes a pilot who tracks the aircraft as it exists in the world, thus making differences in display scale transparent. As a result, tracking performance is predicted to be unaffected by scale differences. Support for the normative model is evidenced in research conducted by Van Olffen, Wickens, and Muthard (2003), who examined tracking behavior with the use of integrated hazard displays of different physical sizes. These researchers reported that pilots exhibit adaptation to changes in display size. Comstock, Glaab, Prinzel, and Elliot (2001) reported similar findings for synthetic vision system displays.

Evidence of Size Contamination in Tracking. While these studies suggest that tracking is unaffected by display size changes, there is a growing body of evidence to indicate the role of size contamination resulting from manipulations to the physical size of a display. Though Van Olffen and colleagues found that display size did not affect tracking of altitude and distance from a lead aircraft, they did observe some contamination to heading tracking, suggesting that the feasibility of the normative model can be questioned. A series of studies that examine flight control with a synthetic vision system display suggest that display minification results in degraded tracking (Prinzel et al., 2002; Stark, Comstock, Prinzel, Burdette, & Scerbo, 2001; Wickens et al., 2003), though the evidence was constrained to specific flight conditions (Wickens et al., 2003), display layouts (Stark et al., 2001), or was inconclusive (Prinzel et al., 2002). More concrete evidence of size contamination resulting from manipulations to physical display size can be found in an experiment conducted by Abbott and Moen (1981). These researchers reported that increasing the size of a cockpit display of traffic information led to reduced error in maintaining a target distance from a lead aircraft. These findings were confirmed in a study by Comstock, Jones, and Pope (2003), who presented pilots with an attitude indicator display in sizes ranging from one to twelve inches wide. Results from this study suggest that flight control error was the highest for the smallest display and that performance continued to improve with display enlargements.

Contamination with axis compression has also been reported in tracking. Specifically, the collective research indicates that individuals underestimate distances along the compressed axis (see above), resulting in underestimates of path deviation and poorer tracking (Barfield, Rosenberg, & Furness, 1995; Boeckman & Wickens, 2001; Ellis, Tyler, Kim, & Stark, 1991; Wickens et al., 1996). The results were mirrored in comparisons of fully expanded two-dimensional coplanar displays with three-dimensional displays. In all cases, the compressed three-dimensional displays were found to result in degraded tracking performance (Andre, Wickens, Moorman, & Boschelli, 1991; Merwin & Wickens, 1996; Olmos, Wickens, & Chudy, 1997; Prevett & Wickens, 1994; Rate & Wickens, 1993; Wickens et al., 1996).

Hence, there is a collective body of evidence to suggest that the size contamination reported in distance estimation extends to the flight control task regardless of the manner in which size is manipulated. Consequently, the normative model is not sufficient to fully describe the effects of display size on tracking. Two alternative models have been proposed to account for why compensation for changes to display size does not occur (Muthard & Wickens, in press).

Resolution Model. The resolution model posits that smaller displays will portray the smallest deviations or movements too minutely to be noticed. Since pilots will be unable to detect these below-threshold deviations, the individual should not exhibit control activity and the deviation would go uncorrected. While display size will influence this threshold, performance above the threshold would not be affected by size. This relationship is depicted in Figure 1.5.1. As tracking is sometimes modeled as an operator's response to the *motion* or velocity of an error signal (McRuer & Jex, 1967), the resolution model is equally appropriate to be applied to motion thresholds as to position thresholds. Because resolution contamination results only because of visual sensory thresholds, the manner in which size is manipulated should not create differences in performance contamination. Thus, to the extent that the ratio of display units to world units remains equal across displays, the magnitude of the performance decrement associated with display minification should not differ, whether size is manipulated by altering physical display size or through axis compression. Conversely, the urgency hypothesis alludes to a cognitive component of tracking.

Urgency Model. The urgency model posits that, for deviations of all magnitudes, smaller display units will suggest smaller errors. To the extent that the pilot views display units as partially indicative of world units, he will correct deviations portrayed on a small display less aggressively than deviations of equal magnitude portrayed on a large display and exhibit greater control error with a minified display (McRuer & Jex, 1967; McRuer & Krendel, 1959; Wickens & Hollands, 2000). Because the pure urgency model posits that the pilot tracks display units rather than world units, the ratio of control response in the small to large display should be equivalent to the ratio of display sizes and, unlike the resolution model, should apply to deviations of all magnitudes. This relationship is plotted in Figure 1.5.2.

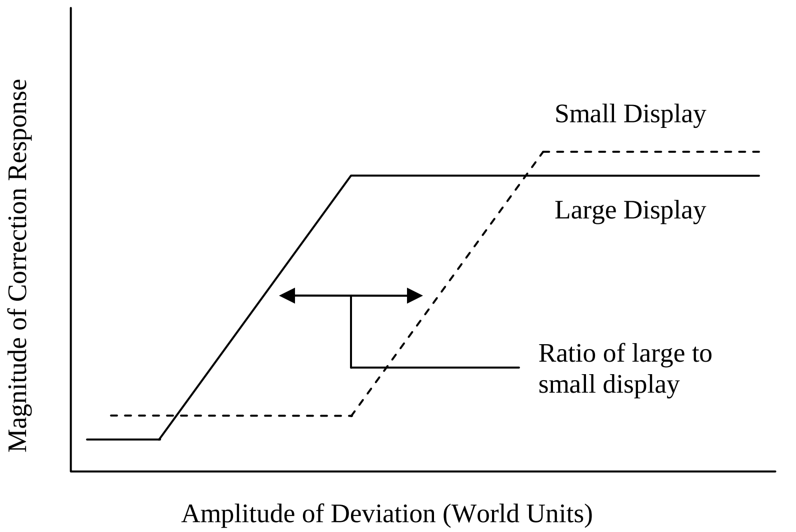


Figure 1.5.1. Depiction of control activity for the small and large displays as a function of error amplitude, as predicted by the resolution hypothesis. Note that, for the small display, the amplitude of the deviation must be larger to induce control response than is the case in the large display. The difference of the curves is also predicted to be equal to the ratio in size of the large to small display.

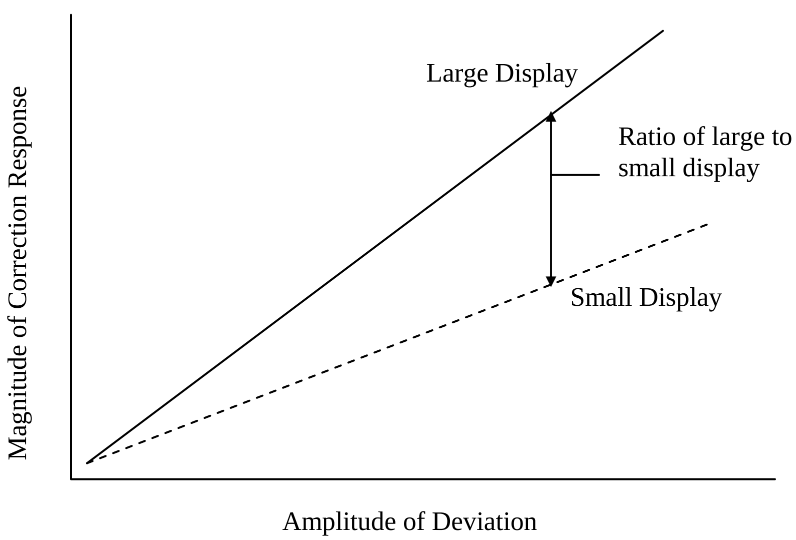


Figure 1.5.2. Depiction of control activity for the small and large displays as a function of error amplitude, as predicted by the urgency hypothesis. Note that the correction response for the small display is always less than that for the large display, regardless of deviation amplitude. The difference of the curves is also predicted to be equal to the ratio in size of the large to small display.

As urgency manifests itself in the allocation of mental and attentional resources, it should be considerably more malleable to display and task differences. One such difference is the pilot's perceived importance of the tracking task (Onstott, 1976). For example, urgency should be greater in instances where a small deviation will result insufficient clearance of terrain than in less terrain challenged environments. Under the urgency model, the magnitude of performance degradation could also be influenced by task demands or by the means of size minification (Boeckman & Wickens, 2001), such as physical display size minification versus axis compression. That is, resolution explanations do not posit any difference in effects as a function of how size is reduced and resolution is lost.

Summary. The normative, resolution, and urgency hypotheses present three unique predictions for tracking error and activity in response to variations of display size. The normative model, which can be used to describe the optimal pilot, predicts that pilots will not be biased by the size of the distance as depicted on the display. Though the resolution and urgency models posit that size will contaminate distance estimates, the underlying cause of the predictions can be differentiated. The resolution hypothesis predicts that tracking will be inferior with the small display, because the smaller deviations will be unnoticeable and sub-threshold. The urgency model, however, posits that tracking will be inferior with the small display, because distances depicted on this display will appear to be smaller and individuals will rely more heavily on display distance information than world distance information. While the resolution and urgency models predict two different contributions of error contamination in tracking, the models are *not* mutually exclusive. Specifically, it is quite possible that visual sensory limitations will inhibit flight control for minute deviations in the small display while larger displayed errors are corrected with greater urgency. It is possible to analytically distinguish the contribution of these models to size effects in flight control by examining the degree of contamination relative to the ratio of display sizes, flight control activity as a function of displayed deviation size, and the extent to which contamination changes with respect to *how* size is manipulated (e.g., through physical size minification or axis compression).

A large body of research has shown that display size does contaminate the tracking task to some extent (Barfield et al., 1995; Comstock et al., 2003; Ellis et al., 1991; McGreevy & Ellis, 1986; Olmos et al., 1997), though the cause of the contamination is unclear. Furthermore, these results have been manifest primarily in three-dimensional axis compression studies and have examined only tracking behavior not coupled with examination of size differences on other estimation, judgment, and decision tasks.

1.6 Decision Making

The decision to select a flight plan centers in part upon accurate estimates of the distances from the pilot's projected path to traffic, terrain, and weather in the airspace. Under a normative model of decision making, a pilot flying under instrument flight rules (IFR) or under the greater authority of free-flight (i.e., unconstrained by air traffic control) would select a flight plan by appraising the value of each flight path. Within the context of aviation, value would minimally be determined through some combination of route safety and efficiency. Safety would be assessed by determining the likelihood that the pilot's aircraft will enter a severe weather system or the protected zone of another aircraft. To make this judgment, a pilot would need to estimate the distance from the aircraft to each hazard and the relative speeds of ownship and the hazard and integrate this information to extrapolate each element's position at a future time or point in space (Schiff & Oldak, 1990). After assessing the values of the possible outcomes, a pilot might optimally compute the *expected* value of each outcome and select the outcome that maximizes this calculated value (Hastie & Dawes, 2001; Von Neumann & Morgenstern, 1947). While this model posits that all available and relevant information should be considered and carefully integrated, it is more likely that a pilot would deviate from this prescribed approach to decision making (Connolly, 1999; Lipshitz, Klein, Orasanu, & Salas, 2001).

Using Distance as a Cue for Safety. As evidenced by the description of the process of normative decision making, selecting a flight path by evaluating and integrating all of the cues in an environment can be cognitively difficult and time consuming. While speed, position, and distance information *should* be used in detecting conflicts with hazards in the airspace, speed information is more difficult to assess than position and distance (Debruyn & Orban, 1988; Mateeff, Dimitrov, Genova, Likova, Stefanova, & Hohnsbein, 2000). The task becomes especially difficult to complete when conflict detection must be made for several hazards simultaneously, particularly when a flight path choice must be made within a short period of time (Muthard & Wickens, 2002, 2003).

In order to overcome these constraints, pilots have been found to employ a *distance heuristic,* in which conflict detection is based primarily on the distance from the hazards to the point at which their trajectories cross at the expense of speed information. Research examining this heuristic has indicated that pilots, when asked to estimate which of two aircraft would reach a designated point more quickly, reported the proximal aircraft would arrive first, regardless of the airspeed of both planes and the actual time to contact (Law, Pellegrino, Mitchell, Fischer, McDonald, & Hunt, 1993). If distance information is the primary criterion used in determining the presence of a conflict, display size biases in distance estimation may result in size contamination in flight route decision making. These issues are detailed in two models that describe the possible effects of display size on route selection.

Normative Model. As in tracking, the normative model describes a pilot who will estimate distance by computationally transforming display units into world units. Providing that the pilot can accurately account for differences in the ratio of display units to world units, estimates of hazard distance and thus route safety should not differ across display sizes. Consequently, any route that is deemed safe to travel when depicted on a large display should also be considered equally safe when depicted on a small display.

Accessibility Model. The accessibility model is analogous to the urgency hypothesis described for tracking. Under this model, resource and time constraints will prevent a pilot from computationally estimating world distances. Conversely, the pilot will use easily accessible display distances as estimates of world distances. These biased distance judgments will translate into biased judgments of risk. For example, a pilot who is estimating the span between ownship and an eminent hazard will likely judge the distance as larger and thus safer when the information is portrayed on a large scale display. On the other hand, hazards portrayed on a small display will appear proximal and more risky.

When translating these estimates of risk to route selection, the accessibility model can predict a *reversal* in path preference in response to changes in display size. Specifically, pilots viewing the hazards and available flight paths on a small display will likely choose to divert around nearby hazards, even if the diversion results in a loss of efficiency. Pilots viewing the same route choice on a large display would estimate that the hazards are a sufficient distance from the shorter route, choosing instead to continue on the route despite potential concerns for safety. Thus, changes in size alone would produce shifts in the decision outcome.

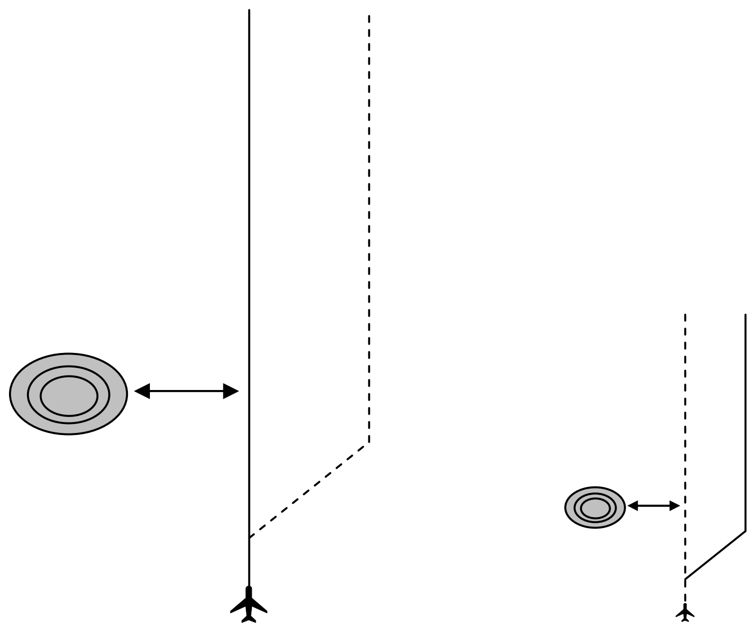
As will be addressed in Experiment 4, Figure 1.6.1 presents an example of such a preference reversal in the context of a graphical representation of the size bias on route selection when size is manipulated through changes to physical size (Figure 1.6.1a and 1.6.1b) and through axis compression (Figure 1.6.1c and 1.6.1d). As shown in the figure, distance estimates from the flight path to the hazard of question are made with a larger display scale when the information is presented on a large two-dimensional display or along the expanded axis of the three-dimensional display. To the extent that scale biases this estimate, it is likely that the pilot will select the efficient planned route when using these displays. When distance estimates must be made with a smaller scale, the distance is presented in a small two-dimensional display or along the compressed axis in the three-dimensional display. If size biases are operating, the pilot will select the safer but less efficient alternate route. No research has been found that has investigated the influence of display size on estimates of risk and route selection.

Summary. The normative and accessibility models provide two descriptive approaches to describing the influence of size on distance estimates used in route selection. While the normative model describes no influence of size, the accessibility model posits that the display scale will bias the estimates of distance used in assessing risk. Consequently, the distance between ownship and a hazard will be overestimated when presented on a large display, resulting in a risky flight path choice, and underestimated when presented on a small display, resulting in a more conservative flight path choice.

1.7 Summary and the Present Study

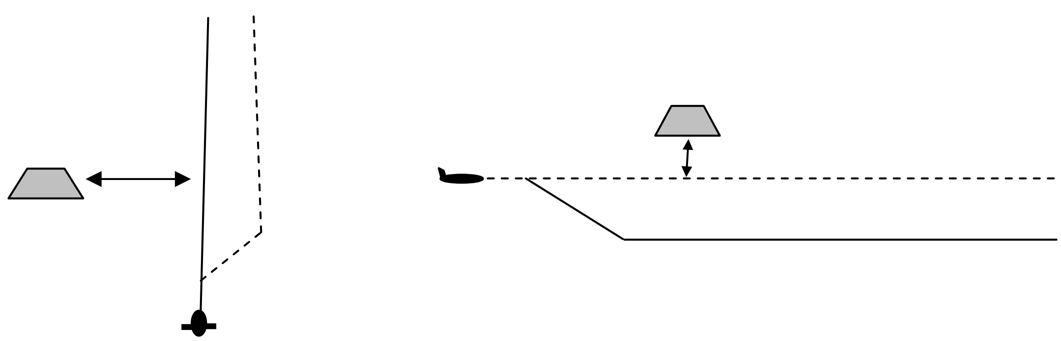
In synthesizing the presented research, it is clear that display size can influence attentional tasks, such as surveillance and search, and spatial distance estimates used in flight control and route selection. Four experiments have been conducted to examine how pilots adapt to shifts in display size in these tasks. All four experiments examined size effects on tracking. In addition, the first pair of experiments (Experiments 1 and 2) focused on the extent to which pilots adjusted attentional scanning patterns to changes in the physical size of a two-dimensional integrated hazard display. The second pair of studies (Experiments 3 and 4) examined the influence that manipulations to display size, either by altering the physical size of a two-dimensional display or through axis compression in a three dimensional display, have on distance estimates used for flight control and flight route selection.

TWO-DIMENSIONAL PHYSICAL SIZE MANIPULATION



(a) Large Physical Size (b) Small Physical Size

THREE-DIMENSIONAL AXIS COMPRESSION MANIPULATION



(c) Large Expanded Axis (d) Small Compressed Axis

Figure 1.6.1. Illustration of accessibility hypothesis and preference reversal. Size is manipulated through changes to physical size (panels a and b) and axis compression (panels c and d). In the small displays (b and d), distance to the mountain is perceived as small and risky, so the less efficient route is chosen. In the large displays (a and c), distance to the mountain is perceived as large and safe, so the efficient route is chosen. Thus, preference is dependent on displayed distance from path to the mountain.

Size and Attention: Experiments 1 and 2. While enlarging the physical size of a display escalates the amount of effort that must be exerted to access peripheral information (Enoch, 1959; Podczerwinski et al., 2001; Wickens, 1992), little research has been done to determine whether pilots will adapt scanning patterns to strategically compensate for these changes. Research is also lacking that has examined the converging costs of legibility and local density clutter with surveillance and search of minified displays. Experiment 1 examined the effect of display size on hazard surveillance and search with an integrated hazard display, which was presented in three display sizes. While flying the aircraft, pilots were asked to continually monitor the display for changes in the movement or altitude of traffic aircraft and weather systems and to periodically search the display for key hazards. Eye movement activity to the regions of the display was also collected as an additional measure of surveillance. Experiment 2 replicated Experiment 1 for the surveillance task without the confounding influence of the search task and examined the interacting effects of size and display clutter.

It was hypothesized that surveillance would be encumbered by the additional effort needed to monitor peripheral display regions when the display was enlarged. Consequently, pilots were expected to exhibit performance consistent with the *effort conservation* hypothesis, rather than strategically compensate for such changes in size. Display minification was also expected to hinder search and surveillance performance by reducing text legibility, especially for highly cluttered displays.

Size and Distance Estimation: Experiments 3 and 4. While computational approaches to distance estimation have been shown to be unbiased by display size (Hartley, 1977), these approaches may be abandoned under time and resource constraints. Because of the *accessibility* of display distance information (Kahneman, 2003), display scale can contaminate world distance estimates, whether size is manipulated by altering physical size (Chapanis & Mankin, 1967; Dixon & Proffitt, 2002; Yang et al., 1999) or through axis compression (Boeckman & Wickens, 2001; Hendrix & Barfield, 1994; McGreevy & Ellis, 1986; Yeh & Silverstein, 1992; Smallman, 2004).

These biased estimates can translate into contaminated flight control, leading to poorer flight control with small scale displays (Abbott & Moen, 1981; Barfield et al., 1995; Boeckman & Wickens, 2001; Comstock et al., 2003; Ellis et al., 1991; Wickens et al., 1996). While research has documented the contamination of flight control with display minification, it is unclear whether size influences performance because of poor display *resolution* or through reduced flight control *urgency*. Experiments 3 and 4 investigated these issues.

Biased estimates might also influence the processes of risk assessment and plan selection in en-route flight planning. While no research has been done to examine the role of display size in these tasks, two hypotheses were proposed. The *normative* model describes a pilot who fully accounts for display scale in estimates of risk and thus makes judgments that are unaffected by display size. The *accessibility* model describes a pilot who assesses world distance influenced heavily by easily accessible display distance, thus overestimating the span between ownship and a hazard when viewed on a large display and underestimating this span when viewed on a small display. As a result, the pilot may exhibit a *reversal* in their flight path *preference*, choosing a riskier route when using a large display but a safer, less efficient route when using a small display.

Experiments 3 and 4 investigated the influence of display size used in flight control and route selection. In Experiment 3, pilots were presented with a simplified flight control display and performed a compensatory tracking task. The size of the display was manipulated through changes to the physical size of a two-dimensional display and through axis compression in a three-dimensional display. Experiment 4 scaled up findings from Experiment 3 to a more realistic flight simulation. In this experiment, pilots were asked to select and travel along a flight plan, using an integrated hazard display and a primary flight display. The safety and efficiency of the two presented routes were varied systematically. Finally, pilots were asked to periodically make judgments of distance and time in response to probes that appeared throughout the trial.

It was hypothesized that flight control would be influenced by display size, resulting in poorer flight control with a minified display. It was unclear, however, the extent to which the effects would be due primarily to reduced resolution or urgency. Performance in estimating distance and time (as estimated from distance divided by speed) in response to the presented probes was expected to be contaminated by display size, at least to the extent that participants experienced time pressure to respond quickly. Consistent with the accessibility hypothesis in decision making, pilots were expected to overestimate the safety of a flight route when it was presented on a large display, relative to the small display. As a result, pilots were expected to make riskier flight route choices when the information was depicted with a larger display scale.

CHAPTER 2: EXPERIMENT 1

Experiment 1 was designed to examine the effects of changing physical display size on distance estimates used in tracking, as well as surveillance and search. Viewing an integrated hazard display, pilots were asked to fly along a prescribed flight route, while monitoring the display for changes in the heading, altitude, or airspeed of traffic aircraft and weather systems. Participants were also asked to periodically search for target hazards in the airspace and answer questions about them. Physical display size was manipulated to produce three display sizes, namely small, medium, and large. With respect to flight control, three hypotheses, which mirror the normative, resolution, and urgency models, can be generated.

1. To the extent that pilots computationally estimate deviations, considering both the presented display distance and the display scale, all three axes of flight control should be unaffected by display size.

2. If tracking error is greater for minified displays, but the decrement is unequal to the degree of display minification and shows an increase only for the smallest amplitude errors, or is nonlinear across the three display sizes, then at least part of the size effect can be attributed to lowered display resolution.

3. To the extent that display minification produces an increase in error equal to the proportion of size reduction, the effect can be fully attributed to the cognitive influence of urgency.

Based on the reviewed literature and the models of effort conservation and strategic compensation, four hypotheses were also formulated for the attentional tasks of search and surveillance.

1. To the extent that display enlargement taxes the available pool of visual resources, the pilot will select an *effort conservation strategy*. As a result, change detection performance should decrease proportionally with display enlargement, and attention allocation to the peripheral display regions as assessed by visual scanning should be reduced disproportionately as display size is increased.

2. If operating, *effort conservation* in search should be apparent in longer probe latencies, particularly when several sources of information must be compared.

3. Probe estimates of both distance and speed should be influenced by display size, such that smaller display scales will lead to underestimates of distance and speed, due to the accessibility of display distance and cognitive complexity of computationally deriving these estimates.

4. To the extent that a *strategic compensation* approach is employed, no difference in change detection performance should be noted as a function of display enlargement. Attention allocation to the most peripheral display regions should also not change as a function of display size.

5. If operating, *strategic compensation* in search should result in no size-related differences in search, despite the extra effort needed to access and compare peripheral information in the larger display.

2.1 Methods: Experiment 1

Participants. Nineteen student pilots from the University of Illinois, Institute of Aviation participated in this study. These pilots ranged in age from 19 to 23 years (M = 21 years) and all were male. The participants had an average of 226 flight hours of experience. Six participants had private licenses, while the remaining thirteen were instrument certified.

Display. Participants were presented with a two-dimensional, top-down integrated hazard display. This display depicted a topographical map, which was based on the National Oceanic and Atmospheric Administration's (NOAA) sectional aeronautical chart, which was overlain with traffic and weather information (see Figure 2.1.1). Ownship was depicted with an aircraft icon that was larger than the traffic aircraft icons and was always located in the center of the hazard display. Additionally, ownship always remained stationary at this location within the display, while traffic and weather moved relative to ownship. An attitude directional indicator, which depicted only pitch, was placed directly below ownship to assist in altitude control. Ownship aircraft heading could be deduced only from the directional heading or angle of the aircraft icon.

Three display sizes were presented to each participant. The small display measured 8.9 cm by 6.4 cm and encompassed 10 by 7 degrees of visual angle. The medium and large displays measured 19.1 cm by 14.0 cm (20° by 15°) and 34.3 cm by 25.4 cm (36° by 27°), respectively. With all changes in display size, the text and icon size of all information present on the display also changed proportionately. Consequently, the ADI encompassed 1.1° by 0.5°, 2.3° by 1.1°, and 4.1° by 2.0° for the small, medium, and large displays, respectively.

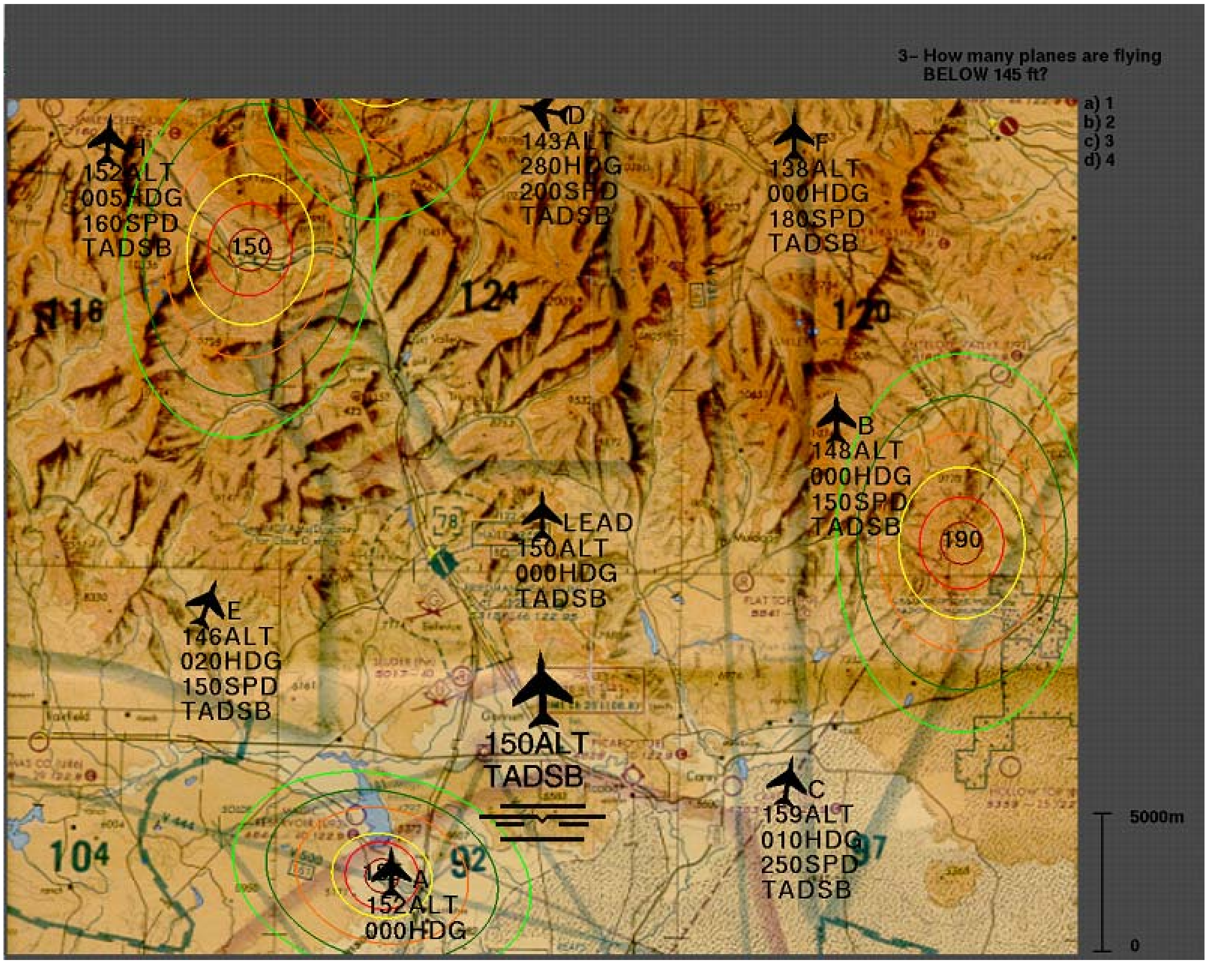


Figure 2.1.1. Integrated hazard display depicting terrain, weather, and air traffic databases. Ownship is the largest aircraft icon located near the center of the display. The aircraft immediately north of ownship is the lead aircraft. Questions were presented in the upper-right hand display corner.

Tasks. Participants were asked to complete three tasks, the first of which centered on maintaining control of ownship in three flight dimensions. Pilots were first required to maintain a target flight level of 15,000 feet and the north-up heading of the aircraft by inputting two axis control maneuvers with a joystick. Altitude information was available directly through the data tag, which was located below ownship, and altitude change information could be accessed through pitch, which could be deduced by examining the attitude directional indicator. Heading was controlled by second order dynamics in response to lateral stick deflection. Heading information could only be determined from the orientation of the ownship icon. Disturbances along all three axes were induced by a quasi-random input with a bandwidth of 0.05 Hz. It is important to note that changes in display size produced changes in the size of the text located in ownship's data tag, as well as the size of the ADI and aircraft icon. In the third dimension of aircraft control, participants were required to maintain "miles-in-trail" distance of 5,000 feet from a lead aircraft by increasing or decreasing ownship airspeed via a thumb switch mounted to the joystick, which produced a constant increase or decrease of speed at 1 knot per button press.

Holding in the throttle button would also cause the aircraft's airspeed to increase or decrease at about 10 knots per second. The target distance of 5,000 feet was depicted in a scale that was located on the right-hand side of the display.

In the second class of tasks, pilots were asked to examine the airspace for changes in the altitude, heading, or airspeed of alphabetically labeled traffic aircraft and weather systems. Implemented changes occurred randomly every fifteen to seventy seconds, and seven changes occurred in each trial. When pilots detected a change, they were instructed to respond by pressing a key and verbally identifying the hazard that changed and the nature of the change (e.g., "Aircraft C changed heading"). Altitude and heading changes were at least 500 feet and 45 degrees in magnitude, respectively. Changes to airspeed were at least 40 knots. It is important to note that, while the location of the changes was carefully dispersed across all regions of the display, the changes did not differ in their *relevance* or importance. Specifically, none of the implemented changes were designed to threaten the pilot's safety by causing a conflict with ownship. However, it should be also be noted that pilots' past experiences would suggest that closer traffic, or traffic located more directly forward of ownship, are more relevant to flight safety, an association which is always present in real flight. Thus, while the relevance of the implemented changes was carefully controlled, the importance of the individual hazards that could change was always coupled with hazard location.

In the final task, participants were asked to answer multiple choice questions about hazards in the airspace, thus generating goal-directed search. Questions appeared in the upper right-hand corner of the display every 40 to 75 seconds. A total of eight questions were included in every trial. Some questions in each trial were designed to require the pilot to make distance or speed judgments. For example, distance questions were phrased, "What is the distance between aircraft C and the center of the weather top at 15,000 ft?). While these questions required the pilot to divide attention across two or more environmental hazards, other questions required the participant to focus attention on a single hazard (e.g., "What is the heading of aircraft F?"). Event timing was constrained so that a change was not presented while the pilot would be engaged in answering the presented question. During the experiment, participants completed one practice trial and six experimental trials. Each trial lasted six minutes, and the experimental session lasted for one hour.

Eye Movement Apparatus. Eye movement data were collected for twelve of the nineteen participants using a Model 501 Applied Science Laboratories integrated eye and head tracker. This apparatus collected both eye and head position at 60 Hz. Analyses revealed no significant performance differences in either event detection, tracking, or search as a function of whether eye data was collected for the participant.

Experimental Design. Performance was assessed as a function of display size in a repeated-measures design. For the task of flight control, measures included altitude root mean square (RMS) error, heading RMS error, and the mean absolute error in tracking the 5000 ft distance from ownship to the lead aircraft. Performance in surveillance was assessed through measures of change detection accuracy and response time, as well as percent dwell time and mean dwell duration to regions of the display as measured through eye movement data. For guided search, measures included question response time and accuracy. Trials were grouped and counterbalanced by display size. Participants completed two trials with each display size.

2.2 Results: Experiment 1

Flight Control. Flight control performance was examined by measuring ownship heading, vertical, and airspeed tracking error. These data are presented in tabular form in Table 2.2.1 and are also presented graphically in Figure 2.2.1. Analyses revealed that decreasing physical display size from medium to small significantly increased heading RMS error by 42% ($F(2, 36) = 16.3$, $p < 0.001$) and altitude RMS error by 81% ($F(2, 36) = 6.8$, $p = 0.003$). Note the nearly twofold increase in vertical tracking error, which mirrored the reduction in the size of the ADI used to estimate vertical tracking error, thus bolstering the urgency model. However, no benefit was found to lateral and vertical tracking when the displays were increased in size from medium to large ($p > 0.10$), suggesting that the decrement found to flight control in the small display may have been due to resolution. Display size also had no effect on miles-in-trail tracking, for which the pilot maintained a target distance from the lead aircraft ($p > 0.10$).

Guided Search. The effects of display size were assessed for performance in answering both focused attention and divided attention questions. While participants did answer focused attention questions more accurately ($F(1, 18) = 183.9$, $p < 0.001$) and more quickly ($F(1, 18) = 53.4$, $p < 0.001$) than divided attention questions, there was no significant difference in accuracy or response time ($p > 0.10$) as a function of display size. Power was low, however, for the accuracy measure ($\phi = 0.13$). Question type and display size did not interact for either performance measure ($p > 0.10$).

Table 2.2.1. Detailed descriptive analyses for the three axes of flight as a function of display size for Experiment 1. The *Comparisons* column describes the significant display size findings. Cells denoted as *NS* represent nonsignfiicant findings. For the altitude and heading measures, display minification from medium to small increased error.

Axis	Statistic	Small	Medium	Large	Comparisons
Altitude	Mean	601.9	330.9	240.4	S > (M = L)
	SE	107.3	87.5	43.3	
Heading	Mean	30.9	21.8	19.0	S > (M = L)
	SE	3.8	2.8	2.7	
Miles-in-trail	Mean	30.7	29.9	29.5	NS
	SE	2.6	2.3	2.7	

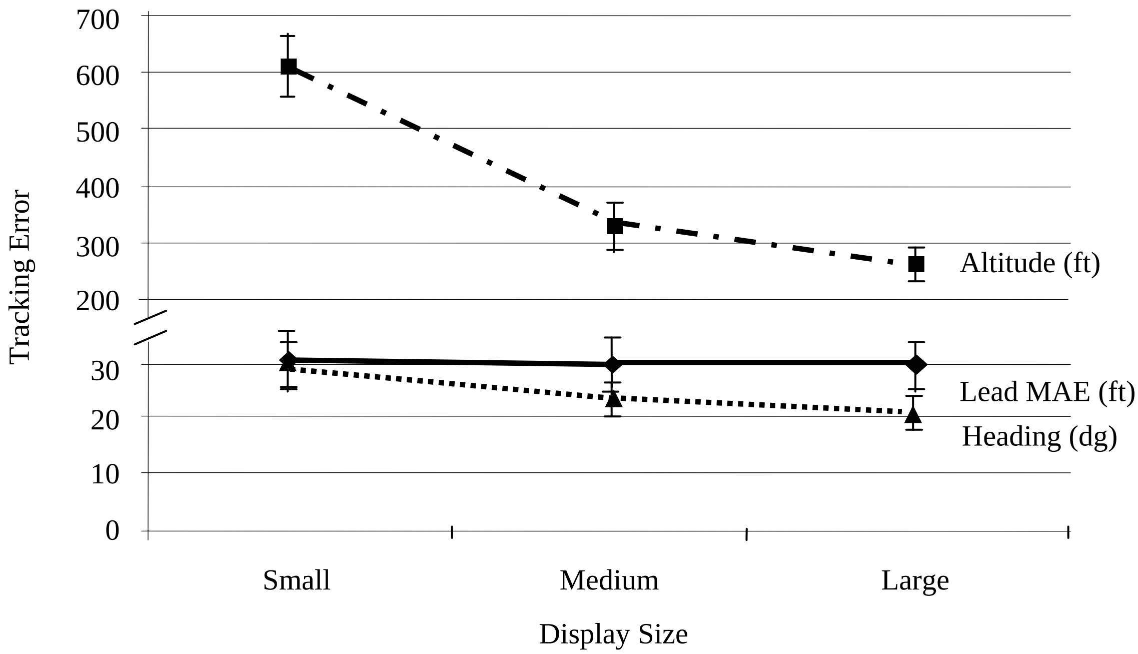


Figure 2.2.1. Flight control error for all three axes of flight as a function of display size. Note that both heading and altitude error significantly increased with display minification from medium to small.

Recall that questions requiring estimates of speed and distance were also included as additional measures of the impact of display size. Analyses for these subsets of questions were conducted and showed that display size had no significant effect ($p > 0.10$) on question accuracy or response time for either distance or speed questions, though again, power was low for these analyses ($\phi < 0.25$ for all tests).

Surveillance. Surveillance was assessed through change detection performance measures. On average, participants detected 12.2% of changes at an average latency of 18.0 s. Analyses revealed that change detection accuracy and response time were unaffected by manipulations to display size ($p > 0.10$). The means and standard errors for detection accuracy and response time are presented in Table 2.2.2. The impact of change eccentricity on detection performance was also assessed by evaluating both accuracy and response time as a function of the distance of the event from ownship. This approach yielded a significant negative correlation between eccentricity and detection accuracy ($r = -0.49$, $p < 0.01$), suggesting that accuracy was significantly reduced with the increasing distance of the changing aircraft or weather system from ownship. Because none of the changes were designed to influence flight safety, this eccentricity effect was present independent of the events' relevance to safe flight. Given that display size had no effect on surveillance performance, the analyses suggest that performance was degraded as changes occurred further from the center of the display. However, display enlargements, which served to further increase the distance between the center of the display and the display perimeter, did not amplify this effect. Thus, the findings suggest that participants strategically compensated scanning patterns to account for the increased display area.

Table 2.2.2. Detailed descriptive analyses for surveillance measures as a function of physical display size in Experiment 1. The *Comparisons* column describes the significant display size findings. Cells denoted as *NS* represent nonsignfiicant findings.

Performance Measure	Statistic	Small	Medium	Large	Comparisons
Accuracy	Mean	8.6	13.4	14.6	NS
	SE	1.7	2.4	2.6	
RT	Mean	23.2	14.1	16.3	NS
	SE	6.0	2.8	2.9	

Eye Movement Data. Eye movement data were collected as an additional measure of surveillance and to examine whether the allocation of attention to different regions of the integrated hazard display differed as a function of display size. To conduct these analyses, the integrated hazard display was divided into three display regions, which are graphically depicted in Figure 2.2.2. The *ownship* region was located in the center of the display and contained ownship, the ADI, and the lead aircraft. Thus, information in this region was used primarily for flight control. The *midrange* and *outer* regions contained hazards that required surveillance.

While the outer region included the most peripheral areas of the display, the midrange region was designated as a ring directly surrounding the ownship display region. Thus, the midrange region represented the area of the display where the pilot could peripherally gain information about flight control while maintaining moderate surveillance of the midrange region.

The first analysis conducted on the eye movement data was an evaluation of percent dwell time to each of the three display regions as a function of size, and these data are plotted in Figure 2.2.3. The greatest proportion of attention was allocated to the central ownship area ($F(2, 20) = 56.1$, $p < 0.001$), reflecting the need to access information for flight control from that region. The proportion of attention allocation to this region increased as the display was enlarged from small to medium ($F(4, 40) = 4.1$, $p = 0.007$), reflecting a shifting in attention from the midrange area to ownship. This shift likely occurred because flight control information, which could be perceived peripherally in the small display when attending to the midrange region, could only be perceived with foveal attention in the larger displays.

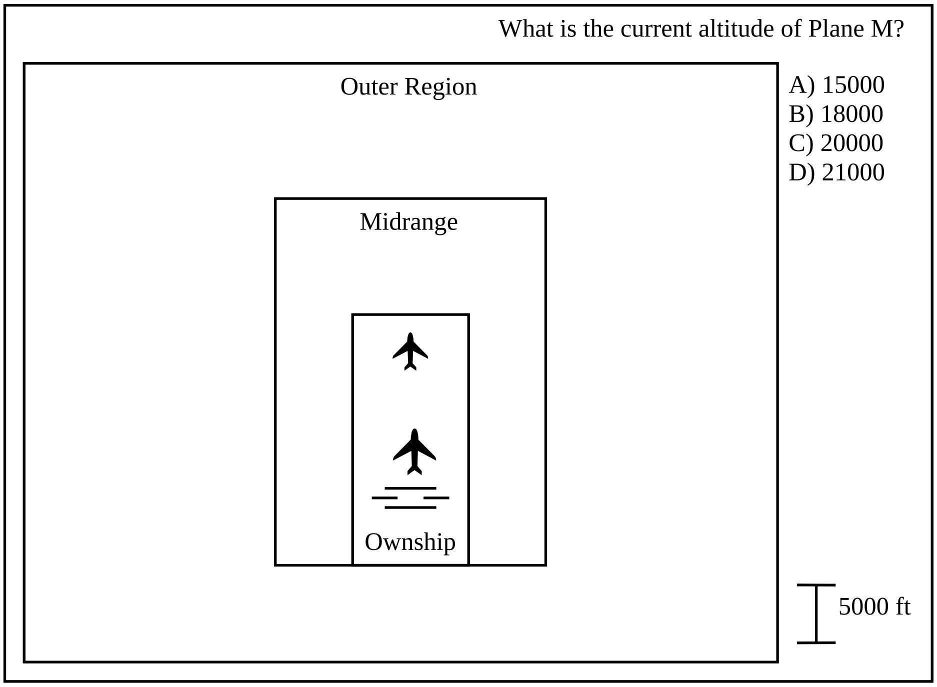


Figure 2.2.2. The location of the ownship, midrange, and outer display regions.

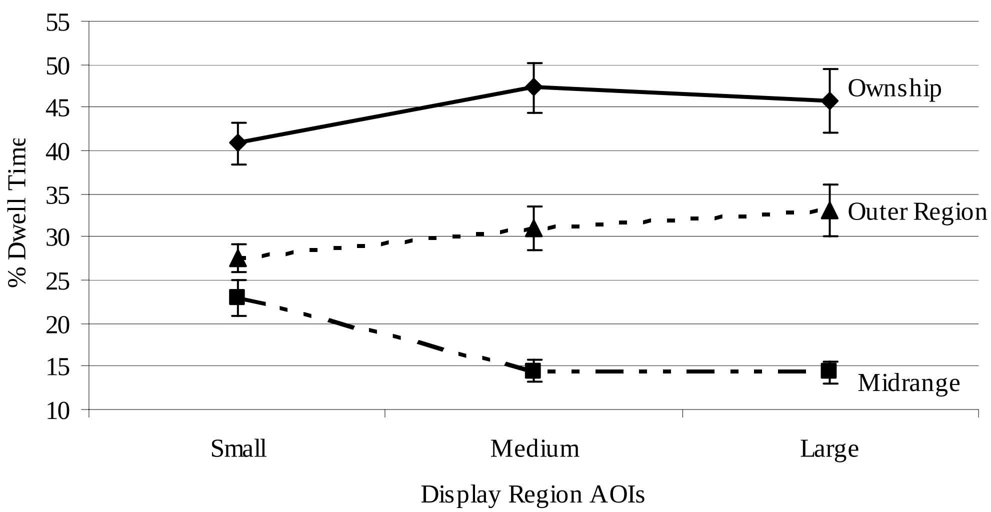


Figure 2.2.3. Percent dwell time allocated as a function of display size and display region. Note the significant increase to the ownship region and reduction to the midrange region with display enlargement from small to medium. No changes were observed when the display was enlarged from medium to large.

The neglect of the midrange region was also evidenced in the finding that pilots allocated a greater proportion of attention to the outermost display region than the midrange area, as shown in Figure 2.2.3. However, when scanning behavior was normalized by a measure of percent/cm^2 (i.e., percentage of time per unit area to be monitored), this measure declined monotonically and significantly from the inner to the middle to the outer ring ($F(2, 20) = 274.0$, $p < 0.001$). Thus, while the outer region receives more total attention, the attention allocation is more sparsely distributed across space, thus accounting for the decrease found in detection performance with greater event eccentricity. Figure 2.2.4 plots the normalized means for each region as a function of display size. As shown in this figure, with enlargements to the physical size of the display, normalized percentage dwell time decreases significantly to all regions, though the effect is more pronounced when the display was enlarged from small to medium than from medium to large and is amplified for the ownship region relative to the other two display regions ($F(4, 40) = 109.9$, $p < 0.001$). This finding is not surprising, since the *amount of information* contained within each region, measured as the number of hazards that could change, is not growing as a function of display enlargement, even though the area to be monitored has been enlarged. Thus, the decrement in normalized PDT across the display regions as a function of display size does not reflect a decrement in attention allocation to the environmental hazards that could change, but rather a simple reduction in the density of those hazards, and thus a corresponding reduction in the density of attention allocation as a function of the display area.

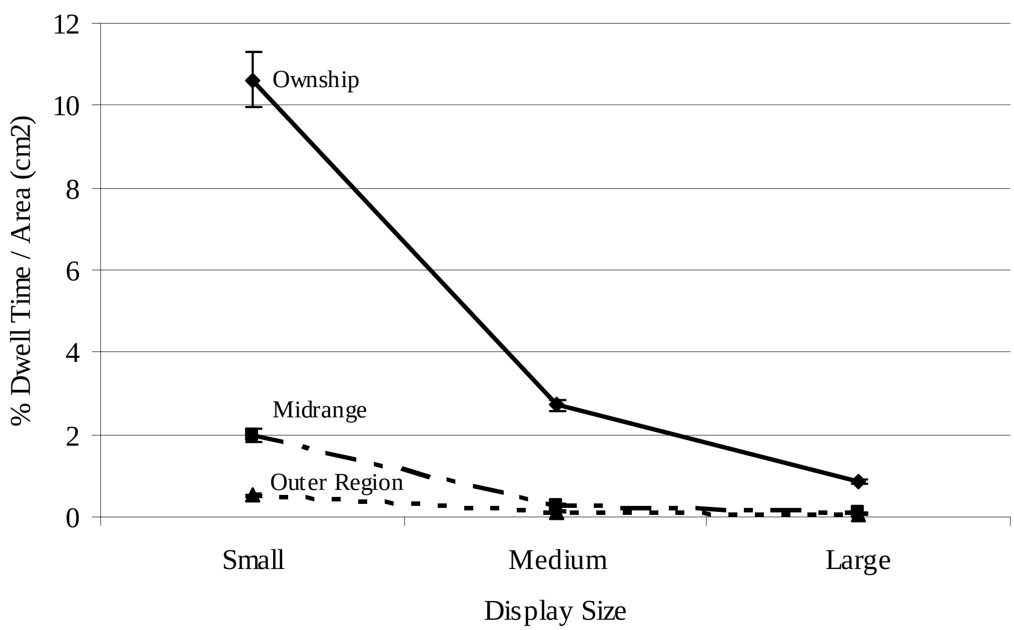


Figure 2.2.4. Percent dwell time to each of the three display regions as a function of display size normalized by the area (in cm) of the display region.

Finally, attention allocation across the three display regions did not change when the display size was increased from medium to large. Additionally, no effect of display size was found for percent dwell time within the outer display region. These results collectively suggest that pilots were effective in widening scanning patterns in response to display enlargements, despite the extra effort that was needed to do so.

The second analysis of the eye data centered on examining mean dwell duration as a function of display size and display region. This analysis was conducted to determine whether percent dwell time differences were found as a result of more scans to a given display region or longer dwells for each visit. These data are plotted in Figure 2.2.5. The figure reveals a pattern of data that is similar to Figure 2.2.3, suggesting that many of the noted differences in percent dwell time are due primarily to differences in the mean dwell duration of fixations to the different display regions. A few differences in the percent dwell time and mean dwell duration data, however, should be noted. First, the main effect for display region ($F(2, 20) = 132.8$, $p < 0.001$) can be attributed to the longer dwells found in the ownship display area. Whereas the percent dwell time data reflected a larger proportion of attention allocation to the outer display region, no difference in mean dwell duration was found in these two regions in the medium and large displays. Thus, the difference in the proportion of attention allocation to the outer region in Figure 2.1.6 was due to a greater number of visits to that region, rather than to greater dwell times.

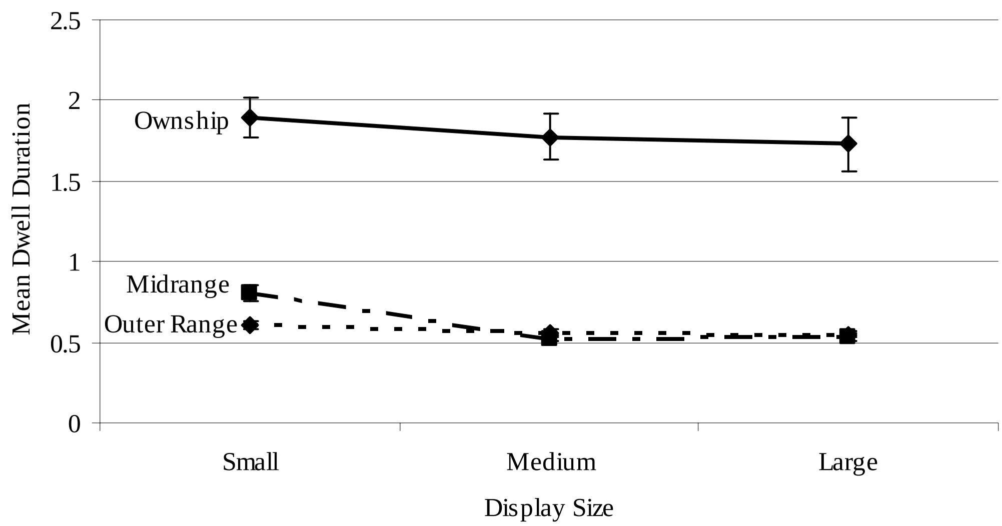


Figure 2.2.5. Mean dwell duration in each display region as a function of display size.

Second, pilots exhibited significantly longer dwells in the smaller display ($F(2, 20) = 5.1$, $p = 0.02$), though this difference was due primarily to the specific increase in dwell duration in the middle region ($t(11) = 5.0$, $p < 0.001$). This finding mirrors the interaction found for percent dwell time, suggesting that the increase in attention allocation to the middle region in the small display is associated with longer dwells there, rather than more visits. This finding provides additional evidence for the hypothesis that pilots were able to access flight control information peripherally from the midrange region when the integrated hazard display was presented in the smallest size. Given that pilots were using a single dwell in the midrange display region to both monitor the airspace and flight control measures, that dwell would be understandably longer.

2.3 Discussion: Experiment 1

Experiment 1 provides an initial examination of the influence of physical display size on the spatial task of tracking and the attention-based tasks of search and surveillance. The effects of display size on flight control were examined as a function of the normative, resolution, and urgency models. Recall that, while the normative model posits no effect of display size on tracking error, the resolution and urgency models postulate that display minification would hinder flight control, though for two distinct reasons. Under the resolution model, display minification would hurt pilots' perception of minute errors causing small deviations to go uncorrected. The urgency model, based in cognition rather than perception, posits that the pilot would correct deviations less urgently with a small display because these deviations would be estimated to be smaller through a process that can be described as *size contamination.*

Findings from the present experiment suggest that display minification resulted in greater tracking error in two of the three axes of control (see Figure 2.2.1). Nevertheless, it is unclear the extent to which this decrement was due to the consequences of resolution or urgency. Evidence for the resolution model is provided by the fact that the increase in error was only seen in the altitude tracking task, whose error was represented by spatial differences in the pitch ladder of the attitude directional indicator. Even more striking is the finding that error was only affected when the display was reduced from medium to small and not from large to medium. Had urgency been the mediating factor in the demonstrated display size effects, the change in error should also have been observed with display minification from large to medium and should have been proportional to the degree of display minification. While the presented findings suggest this was the case for altitude tracking with display minification from the medium to small display, the miles-in-trail tracking measure failed to reflect the same proportionality. Regardless of whether display minification hindered flight control because of resolution, urgency, or a combination of these two factors, it is the case that participants did invest more effort when tracking heading and altitude with medium and large displays than with the smaller display. These findings are consistent with the literature that has demonstrated that display minification resulted in poorer tracking (Abbott & Moen, 1981; Comstock et al., 2003) and, given that the literature in this area was sparse, helps to strengthen the conclusion that display size influences estimates of path deviation and the resultant task of flight control.

In addition to examining flight control performance, the present experiment was designed to examine the effects of physical display enlargement on search and surveillance within the context of the effort conservation and strategic compensation models. Display enlargement was found to have almost no influence on search, on the spatial judgments derived from that search, or on overall surveillance. For these attentional tasks, pilots were thus found to strategically compensate for enlargements to the physical size of the presented display by engaging in longer scans and allocating a greater proportion of attention to the outer region of the display (see Figure 2.2.3). In essence, analogous to the zoom lens model of attention (Ericksen & St. James, 1986), pilots were found to broaden their attentional spotlight to compensate for the increase in overall display area. This adaptation also came without performance cost, replicating effects from other visual search studies (e.g., Teichner & Mocharnuk, 1979).

Strategic compensation was also demonstrated in the shift of attention from the middle range of the display to the ownship region with display enlargement. Thus, while pilots could peripherally access tracking information in the small display from the midrange region, they abandoned this strategy in favor of directly foveating the ownship region when the display was enlarged. Additionally, even though pilots showed longer dwells in this central area, attention to the outermost region of the display was maintained. While it may be argued that this enhanced concentration of attention in the center region of the medium and large display (see Figure 2.2.3) was responsible for the reduced tracking error with these displays (see Figure 2.2.1), it is doubtful that this was the case because the degree of tracking improvement was not proportional to the degree of scanning enhancement and was not found for all three tracking axes. Additionally, further evidence from Experiment 2 will show this to be implausible.

While pilots were successful at adapting surveillance patterns to enlargements in the physical size of the display, it should be noted that such modifications did not come without cost. Recall that the strategic compensation model posited that pilots would invest the extra effort needed to survey a larger display area. The urgency model of tracking also suggested that pilots would use more resources to more actively and urgently control deviations portrayed on large displays. Thus, the increased control urgency and widened scanning patterns observed with display enlargement could only have been possible with an increase in the pilot’s resource investment in the tasks. Consequently, these approaches may be employed less frequently or less successfully to the extent that the tasks become more difficult or more numerous or to the extent that available resources are low. Under these resource-limited conditions, pilots would be predicted to employ a less demanding strategy, exhibiting control performance more indicative of the resolution or normative models and surveillance behavior more representative of the effort conservation model.

Furthermore, very few head movements were made, even in the largest display, which spanned 36 degrees laterally. This finding is not in disagreement with the literature, which has shown that the point at which head movements must be made to access information begins at magnitudes as great as 90 degrees (Sanders, 1970). However, more moderate estimates collected in more naturalistic environments, suggest the threshold begins at 20 degrees of visual angle (Bahill et al., 1975), and should thus be considered when determining optimal display size. To the extent that a display, sized equally to the large display used in the present experiment, induces head movements, a strategic compensation approach in surveillance may become less feasible. An additional restriction centers on the possible contamination of display surveillance by the presented search probes. Because participants were periodically probed to search for and answer questions about display elements, this task may have unnaturally driven surveillance patterns to regions of the display that would not have been monitored had the search probes not been present. In order to examine surveillance uncontaminated by search, Experiment 2 was conducted to examine the influence of display size on change detection without the presence of confounding search probes. A second variable was also added in that display clutter was amplified in half of the trials to determine whether display minification would amplify local density clutter decrements to surveillance.

Finally, while the relative distribution of attention in the search task was not influenced by display size in Experiment 1, this manipulation also had no influence on the distance and speed estimates that were derived from the search. While it was initially hypothesized that these estimates would be biased by the accessibility of display distance information (Kahneman, 2003) and would thus be underestimated when the display scale was reduced relative to estimates made with the large display, the analyses suggest that responses were not affected. Based on these initial data, we can conclude that pilots used a computational approach to this explicit estimation, basing estimates of world distance and speed on display distance and display scale information rather than a display distance substitution strategy (Hartley, 1977). When collectively considering these results in conjunction with those of flight control presented above, the analyses suggest that estimates made without time stress can utilize both display distance and display scale information, while time constraints and implicit estimations such as those used in tracking may induce pilots to become reliant upon display distance alone for estimation. This issue will be explored in more detail in Experiment 4.

CHAPTER 3: EXPERIMENT 2

Experiment 2 was conducted to investigate the presence of the strategic compensation approach in surveillance, without the presence of search probes. To intensify the difficulty of the surveillance task and examine the interacting effects of display minification and local density clutter, the number of aircraft presented on the display was increased on some trials. Finally, flight control was again examined as a function of the three tracking models. The hypotheses generated for flight control can be refined based on the obtained data from Experiment 1.

1. Minifying a display should result in size contamination, at least for some of the axes of flight control.

2. To the extent that the degree of contamination is less than the degree of minification, and/or the control decrement is nonlinear across the three display sizes, the effect can be attributed to resolution.

3. To the extent that the magnitude of contamination is proportional to the degree of display minification and is linear across the three display sizes, the observed contamination can be attributed to resolution.

The hypotheses for the surveillance data are founded in the presented model of strategic compensation, which was shown to be the primary approach to surveillance used in the previous experiment. An additional hypothesis is proposed as a prediction of the possible negative effects of clutter.

1. Pilots should exhibit strategic compensation for enlargements in display size. This approach will be reflected in equal surveillance performance and equivalent attention allocation (visual scanning) to the peripheral display region as a function of display size.

2. As an additional form of strategic compensation, pilots should be found to reallocate attention from the middle display region to the ownship region with display enlargement

in order to directly access tracking information, rather than attempting to access it peripherally.

3. Amplified display clutter should hinder surveillance performance, particularly for the smallest display, where density would be highest and lateral masking would be most likely to occur. To the extent that display density results in information occlusion or reduced readability, longer dwells might also be hypothesized to result.

3.1 Methods: Experiment 2

Participants. Twenty-nine student pilot participants from the University of Illinois, Institute of Aviation participated in the study. Twenty-three of the pilots were male, while the remaining six were female. The pilots ranged in age from 19 to 23 years (M = 21 years). The participants had an average of 130 flight hours of experience. Seventeen participants had private licenses, while the remaining twelve were instrument certified.

Displays. The integrated hazard display was identical to that used in Experiment 1 with a few exceptions. In Experiment 2, ownship was depicted with a blue aircraft icon, rather than a black icon. While in Experiment 1 the ADI depicted only pitch information, this instrument was updated in the present experiment to include both pitch and roll information. Thus, while long-term heading information could still be deduced from the angular orientation of the pilot's ownship aircraft icon, short-term heading orientation information could also be determined by examining the ADI thereby lessening the demands on heading control. Thirdly, the location of ownship was moved up slightly so that it was located exactly in the center of the display rather than being located somewhat below center, as was the case in Experiment 1.

In the final change for Experiment 2, additional hazards were added to half of trials as a manipulation of display clutter. In low display clutter trials, eight aircraft and seven weather systems were present in all trials. In high display clutter trials, however, fifteen aircraft were added. Because these aircraft were added to increase only the visual clutter of the display, rather than also increase the memory load of the pilot, these aircraft never changed heading, altitude, or airspeed, and thus the pilot was not required to monitor them during the trial. To indicate this distinction, these clutter aircraft were lowlighted and no information was present in their data tags. An example of a cluttered display is shown in Figure 3.1.1.

Tasks. Pilots were asked to complete the tracking and change detection tasks described in Experiment 1. A few small changes were made to each of these tasks. For the tracking task, pilots were asked to maintain a separation of 7 miles, rather than 5 miles, from the lead aircraft. The separation distance was increased so that pilots would make a more true distance estimate, rather than simply estimating the length of the presented scale, which depicted 5 miles. In the change detection task, the airspeed changes were removed, and pilots were asked to detect only heading and altitude changes for traffic and weather systems. Airspeed changes were not included in Experiment 2, because they were detected quite poorly in the initial experiment. Heading changes could be seen either by noting a change in the orientation and movement of an element, while altitude changes were indicated with a change in the digital datatag. Twelve changes were implemented in each trial, allowing for three changes to aircraft heading, aircraft

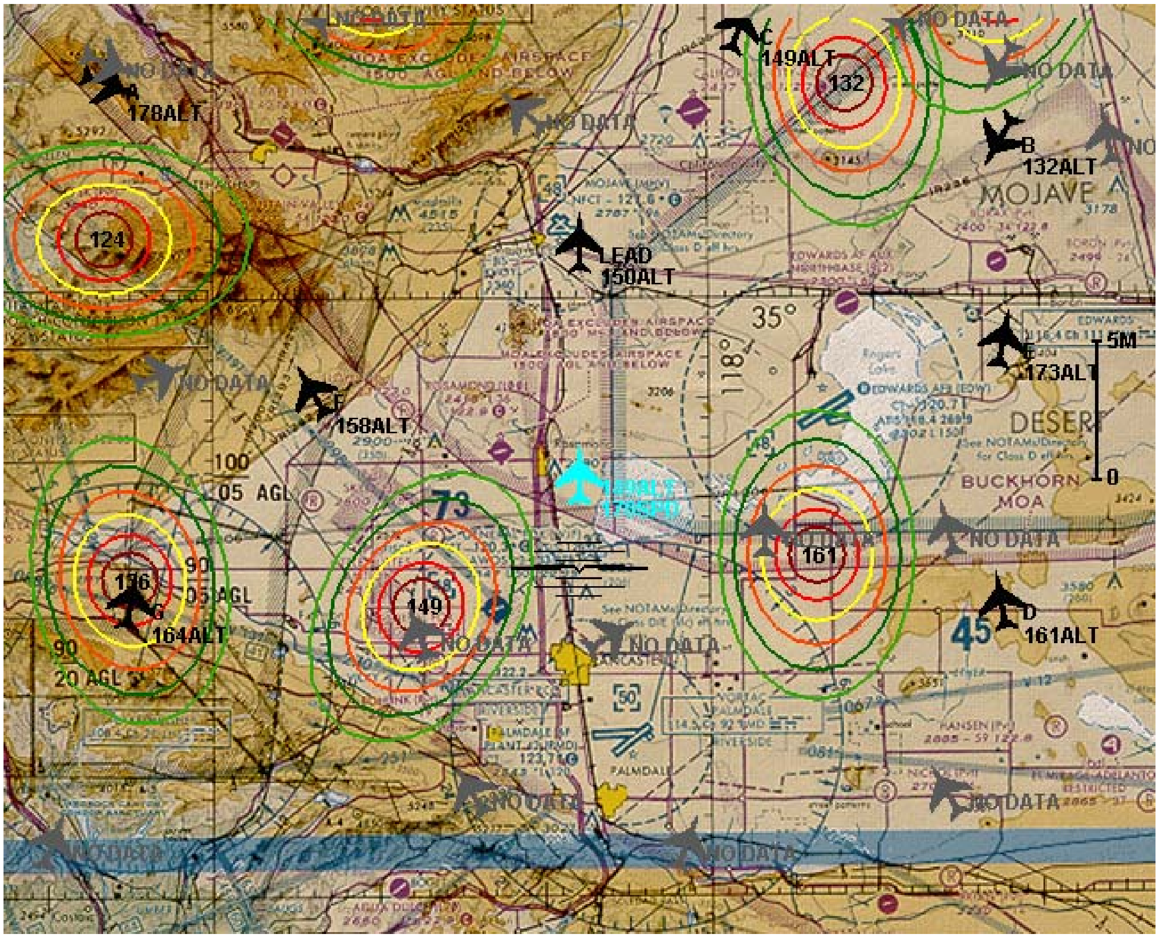


Figure 3.1.1. Integrated hazard display depicting terrain, weather, and air traffic databases. Display clutter was increased by adding lowlighted irrelevant aircraft with data tags reading "No Data."

altitude, weather heading, and weather altitude in each trial. Changes occurred randomly every 25 to 45 seconds. The question task, described in Experiment 1, was eliminated in Experiment 2, so that visual search did not contaminate the surveillance measures. During the experiment, participants completed one practice trial and twelve experimental trials. Each trial lasted six minutes, and the experimental session lasted for one hour.

Eye Movement Apparatus. Eye data was successfully collected for 20 of the 29 participants. The eye movement apparatus used in the present experiment was identical to that used in Experiment 1. No significant differences were found in event detection or flight control performance as a function of whether eye data was successfully collected for the participant.

Experimental Design. Performance in the surveillance and tracking tasks were assessed as a function of both display size and clutter in a repeated-measures design. Trials were grouped and counterbalanced by display size and clutter. Participants completed two trials for each display size and clutter combination.

3.2 Results: Experiment 2

Flight Control. As with Experiment 1, flight control performance was assessed by examining altitude and heading RMS error, as well as miles-in-trail mean absolute error. These data are plotted as a function of display size in Figure 3.2.1 and are shown in tabular form in Table 3.2.1. Reducing physical display size from medium to small (roughly halving the size) significantly increased altitude error ($F(2, 56) = 19.1$, $p < 0.001$), though the increase in error reached only 56%, which was less than that found in Experiment 1 (81%). No size effect was found for heading ($p > 0.10$), despite the presence of size contamination for this measure in the previous experiment, though Figure 3.2.1 does reveal the nonsignificant trend for error to increase monotonically with minification. Given that roll information was available in the ADI in the present experiment, but not in Experiment 1, the muted effect of size on heading has interesting implications. Specifically, these data suggest that additional detailed information about roll used in heading control reduced the decrement associated with display minification and may have reduced a resolution decrement which existed when only limited information was present.

Table 3.2.1. Detailed descriptive analyses for the three axes of flight as a function of display size for Experiment 2. The *Comparisons* column describes the significant display size findings. Cells denoted as *NS* represent nonsignfiicant findings. For the altitude and miles-in-trail measures, display minification from medium to small increased error.

Axis	Statistic	Small	Medium	Large	Comparisons
Altitude	Mean	474.6	303.7	291.2	S > (M = L)
	SE	60.6	40.1	36.2	
Heading	Mean	18.5	17.3	15.7	NS
	SE	1.9	1.5	1.5	
Miles-in-trail	Mean	4252.6	3447.2	3965.0	S > (M = L)
	SE	186.1	198.9	238.0	

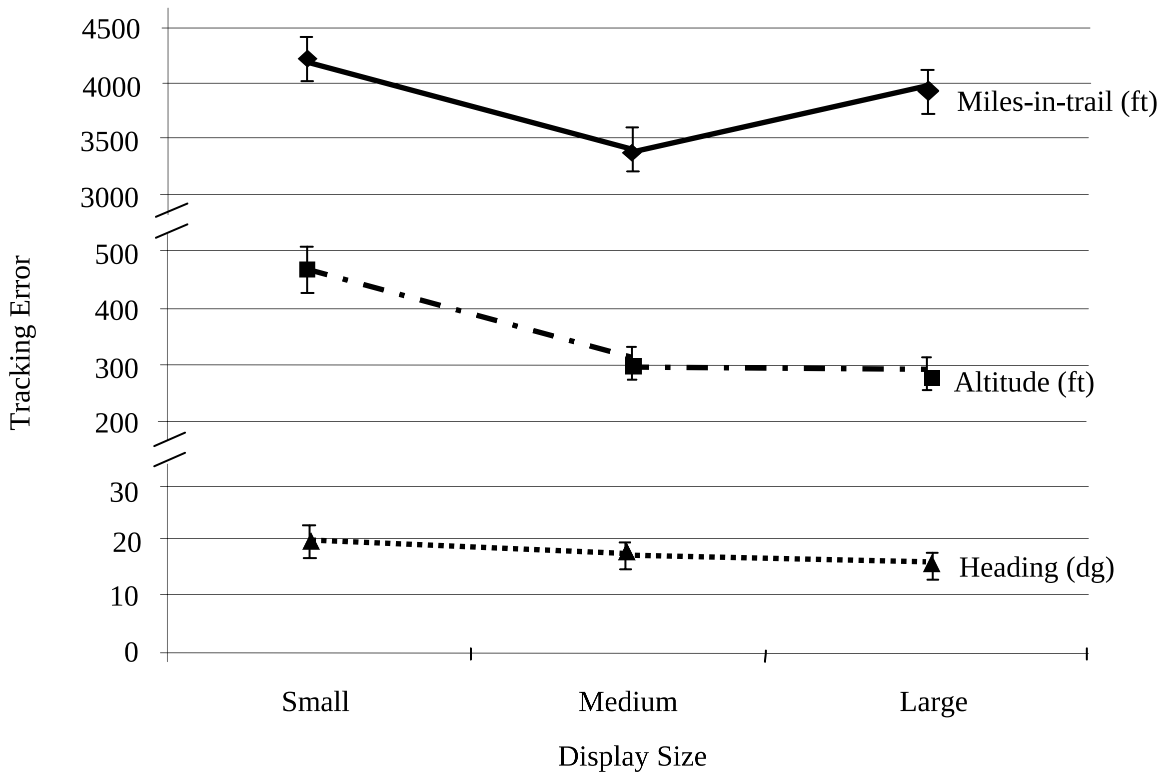


Figure 3.2.1. Flight control error for the three axes of flight as a function of display size. Note that control error for altitude and miles-in-trail was reduced when the display was enlarged from small to medium.

In contrast to heading tracking, size *did* influence the control of miles-in-trail, indicating that reducing size from medium to small produced a 23% decrement to performance ($F(2, 56) = 3.6$, $p = 0.03$). While there appeared to be a small increase in error when the display was enlarged from the medium to large size, the difference was not significant ($p > 0.10$). Thus, a size decrement was present in miles-in-trail tracking that was not found in Experiment 1, while the heading effect found in the previous experiment was not replicated here. It is possible that pilots viewed heading in the present experiment as the axis of primary concern, devoting relatively more resources to this task and thus succumbing to size contamination for tracking in the miles-in-trail and altitude axes.

Surveillance. As in Experiment 1, display surveillance was assessed by examining change detection accuracy and response time. Figure 3.2.2 and Table 3.2.2 presents the accuracy data as a function of physical display size and display clutter. As shown in the figure, display size had no overall effect on surveillance accuracy ($p > 0.10$), thus replicating findings from the initial experiment and bolstering evidence for strategic compensation of scanning in response to display enlargement, even without the presence of search probes. Conversely, display size and clutter were found to significantly interact ($F(2, 56) = 9.3$, $p < 0.001$), indicating that when display clutter was increased, a 30% decrement to change detection was found only in the small display, reflecting the negative costs of local density clutter in the minified interface. Size and clutter had no significant effect on change detection response time ($p > 0.10$).

Event detection accuracy and response time were also examined as a function of the distance of the event from ownship, which was assumed to be the primary focus of attention. Both performance measures were found to be significantly, though only modestly, correlated with event eccentricity ($r = 0.15$, $p < 0.01$ for accuracy; $r = 0.15$, $p < 0.001$ for response time). Given that all events were of equal relevance, the data indicate that the displacement of events from ownship can be associated with a small reduction in change detection accuracy and latency. To examine whether event detection was superior for hazards that were located directly in front or to the side of ownship, relative to less relevant hazards behind ownship, event detection was also assessed as a function of display area. For this analysis, the display was partitioned into regions located in front of, to the left or right of, and behind ownship. Analyses revealed that event detection accuracy was superior for the side regions, relative to detection for events located behind or in front of ownship ($F(2, 56) = 5.6$, $p = 0.006$), suggesting that pilots might have perceived hazards in these regions as most relevant. Conversely, event detection response time was equal for events located in the front and side regions relative to ownship, but suffered for the region located directly behind ownship, likely because hazards in this area were perceived as less important ($F(2, 52) = 3.0$, $p = 0.06$, marginally significant). Thus, while the implemented *events* were equally relevant, these findings suggest that hazards located in front and to the side of ownship might be perceived as more relevant than those located behind.

Collectively, the findings of the lack of effect of display size on event detection suggests that, while pilots neglected allocating attention to the display periphery, they did so equally across displays sizes. Thus, these data strengthen the findings from Experiment 1, suggesting pilots strategically compensate for display enlargements, even without the confounding effects of search probes. While these conclusions are based solely on performance analyses, examining the eye movement data can provide more concrete evidence for this approach in actual saccadic behavior.

Eye Movement Data. As in Experiment 1, the eye movement data were assessed as a function of display region. Because the location of ownship was shifted upward relative to the previous experiment, these display regions were reallocated slightly. Figure 3.2.3 presents a graphical depiction of these regions. As shown in the figure, the portion of the midrange region that was located ahead of ownship in Experiment 1 was shifted behind ownship in the present experiment. The size of the regions remained equivalent to those specified in the previous experiment.

Table 3.2.2. Detailed descriptive analyses for surveillance measures as a function of physical display size and clutter in Experiment 2. The *Comparisons* column describes the significant display size findings. Cells denoted as *NS* represent nonsignfiicant findngs. Note that clutter reduced detection accuracy, but only for the small display.

Performance Measure	Display Size	Statistic	Low Clutter	High Clutter	Comparisons
Accuracy	Small	Mean	8.6	23.2	Low < High
		SE	2.1	1.9	
	Medium	Mean	13.4	14.1	NS
		SE	1.9	2.0	
	Large	Mean	14.6	16.3	NS
		SE	1.3	2.0	
RT	Small	Mean	10.2	9.9	NS
		SE	1.2	1.6	
	Medium	Mean	9.0	11.0	NS
		SE	0.9	1.3	
	Large	Mean	11.0	10.0	NS
		SE	1.1	1.2	

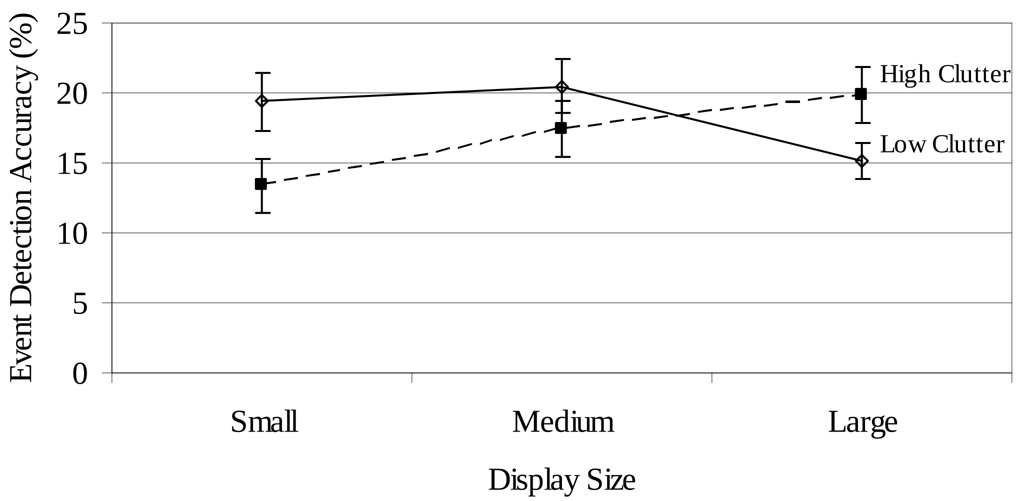


Figure 3.2.2. Event detection accuracy plotted as a function of display size and display clutter. Note that high clutter only reduced event detection for the small display.

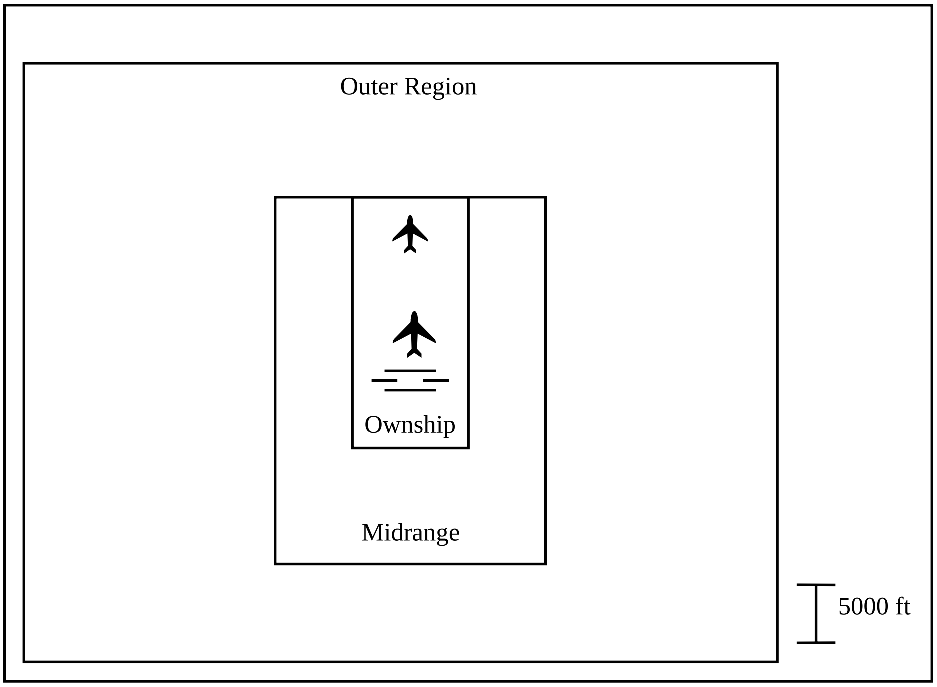


Figure 3.2.3. The location of the ownship, midrange, and outer display regions. Note the difference in the location of the midrange region from that shown in Figure 2.2.2 for Experiment 1.

Percent dwell time to each of the display regions was assessed in a repeated measures ANOVA as a function of display size, display region, and clutter. As clutter did not significantly affect percent dwell time, the data were collapsed across the two conditions of display clutter. The analyses for display size and display region produced strikingly similar results to those found in Experiment 1 and are depicted in Figure 3.2.4. The first thing to note is that on average 45.2 % overall dwell time was spent in the ownship region, which was significantly greater than the allocation of attention to either the midrange (17.7%) or outer range (31.0%) regions ($F(2, 36) = 41.3$, $p < 0.001$). These findings again confirm the importance of this region for gaining information essential for flight control and also support the identification of the area as the primary focus of attention. Second, the outer display region received a significantly greater proportion of attention than the midrange region, at least when the display was presented in a medium ($t(19) = 6.1$, $p < 0.001$) or large size ($t(19) = 8.4$, $p < 0.001$). As in Experiment 1, however, normalizing percent dwell time by the area to be monitored reversed this finding ($F(2, 36) = 237.3$, $p < 0.001$). Thus, attention allocation was more *sparsely* allocated across the outer display region than the midrange display region, accounting for the negative effect of event eccentricity reported for the change detection analyses. Also replicating findings from Experiment 1, PDT normalized as a function of region area (PDT/cm^2) to each region was found to significantly decrease with display enlargement ($F(2, 36) = 497.0$, $p < 0.001$). As stated previously, while display enlargement increased the eccentricity of environmental hazards and reduced the density of these hazards across the display area, it did *not* produce a change in the amount of relevant information within each region. Thus, it is not surprising that a decrement to normalized PDT was found, as it reflects stability in PDT to each hazard, while the size of the display region was enlarged.

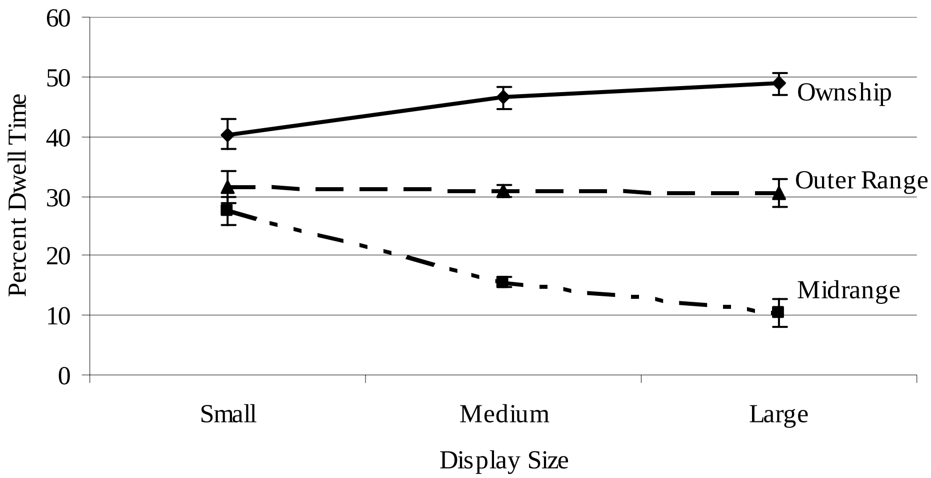


Figure 3.2.4. Percent dwell time for the three display regions as a function of display size. As in Experiment 1, PDT to the ownship region decreased while PDT to the midrange region increased with display enlargements from small to medium.

Interestingly, the allocation of attention to the ownship and midrange regions were again mediated by display size ($F(4, 72) = 17.5$, $p < 0.001$). Specifically, an enlargement in the physical size of the display resulted in a shift of attention away from the midrange region to the ownship region, again reflecting, we assume, the finding that display enlargement prohibited pilots from accessing flight control information peripherally while fixated on the midrange region. Thus, when the display was enlarged from small to medium, pilots chose instead to direct attention directly to the ownship region for flight control. As in Experiment 1, attention allocation to the outer display region was unchanged by display size, despite the extra effort that was needed to extend surveillance patterns to these peripheral regions. Clutter, alone or as an interacting factor with size, did not influence percent dwell time measures ($p > 0.10$).

To examine the extent to which these differences in percent dwell time were due to longer dwells in each region or longer saccades, mean dwell duration was also subjected to a repeated measures ANOVA. The results of this analysis are shown in Figure 3.2.5. As in Experiment 1, mean dwell duration for the ownship region was significantly longer (1.5 s) than the midrange (0.6 s) or outer display regions (0.2 s) ($F(2, 36) = 132.8$, $p < 0.001$). Display enlargement from the small to the medium display, also produced a reduction in the duration of dwells to the midrange display region, replicating findings from the previous experiment ($F(4, 72) = 11.6$, $p < 0.001$). Interestingly, dwells in the midrange region were also significantly reduced when the display was enlarged from medium to large ($t(19) = 2.7$, $p = 0.01$), and this reduction was accompanied by a lengthening of dwells in the ownship region ($t(19) = 2.3$, $p = 0.03$). These data provide further evidence for the shifting of attention in the midrange region with smaller displays, in which flight control information could be gained peripherally, to the direct allocation of attention to the ownship region in the enlarged displays. Display enlargement did not significantly affect dwell duration to the outer display region ($p > 0.10$). Mean dwell duration was also not affected by added display clutter ($p > 0.10$).

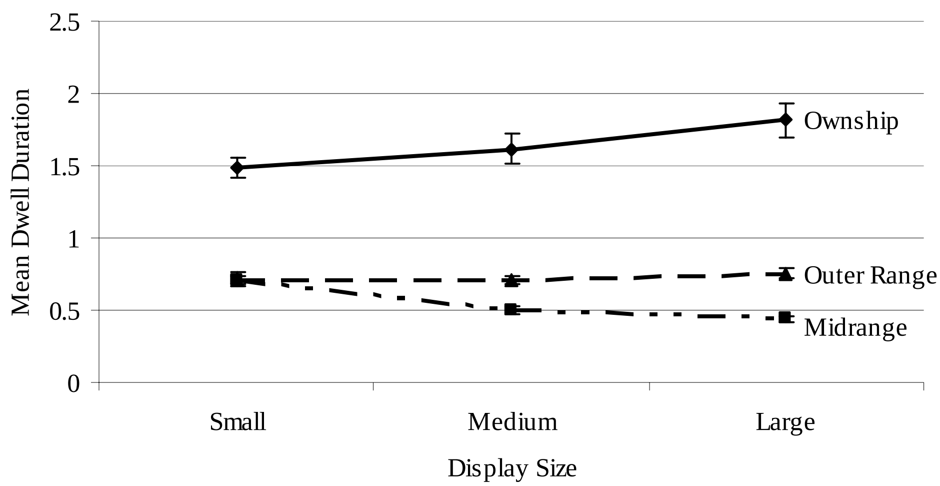


Figure 3.2.5. Mean dwell duration in each of the three display regions as a function of size. Duration in the ownship region increased with display enlargements, while those in the midrange regions were reduced.

3.3 Discussion: Experiment 2

Experiment 2 provides a replication of the size contamination of flight control from Experiment 1, as well as a validation of the strategic compensation approach to surveillance without the presence of confounding search probes. For flight control, size contamination was again observed for the vertical axis as well as for the miles-in-trail control axis. As in Experiment 1, the degree of contamination was less than the degree of display minification and was only observed when transitioning from the medium to the small display, suggesting that contamination may have resulted from limited resolution for the minute errors in the smallest display. Further evidence for the resolution model can be found in the discovery that size contamination of heading control, present in Experiment 1, was eliminated in the present experiment. Specifically, recall that while roll information was not present in the ADI in Experiment 1, this information was accessible from the ADI in Experiment 2 and would have provided more detailed predictive information both about the current orientation of the aircraft and its influence on the aircraft's future deviation. Thus, presenting this more detailed deviation information likely counteracted the limiting effects of minification on perceptual resolution.

While the evidence suggests a strong effect of resolution in the hindering effects of minification, the influence of the more cognitive factor of urgency still cannot be completely ruled out. In both Experiment 1 and Experiment 2, only two of the three axes of flight were contaminated by display minification. Thus, it is possible that pilots were prioritizing the axis that did not reflect contamination (miles-in-trail in Experiment 1, heading in Experiment 2), at the expense of the other two axes. Consequently, while all resources were invested to ensure the prioritized axis was tracked properly by estimating deviations in world units, the pilot was biased by display scale for the remaining control axes. In addition, the degree of size contamination was less for Experiment 2, where only one concurrent task was being performed, than for Experiment 1, where both search and surveillance tasks were performed. This latter finding suggests that reducing the number of concurrent tasks allowed pilots to allocate a greater number proportion of resources to the flight control task, thus reducing the degree of size contamination and providing evidence for the resource-based model of urgency. Specifically, the resource scarcity associated with the tasks in Experiment 1 lead to a greater influence of size contamination.

Given the data presented in the first pair of experiments, several conclusions can be drawn regarding the effects of display minification on flight control. First, display minification can be associated with a reduction in flight control, at least along axes of control that are not given priority (Abbott & Moen, 1981; Comstock et al., 2003). When display minification does result in contamination, the magnitude of the contamination is generally not as great as the degree of size minification and is generally observed only when the overall display is reduced to less than twenty degrees of visual angle, and the ADI alone is less than 2 degrees of visual angle. Finally, while the underlying cause of contamination can be attributed in part to a reduction in display resolution and limitations in the perceptual system to identify minute deviations, some of the effect may also be caused by differences in urgency and resource allocation when tracking with smaller displays. Experiments 3 and 4 will provide a more detailed examination of these issues.

While size was clearly found to influence flight control behavior and performance, pilots were successful at adapting to display enlargement in the surveillance task. Though this approach could have been attributed in part to search probes which unnaturally influenced surveillance in Experiment 1, strategic compensation was still evidenced in the performance and eye data in the present experiment, in which no probes were present. Specifically, pilots were found to effectively allocate attention to the most peripheral display region, despite the extra effort that was required to do so (see Figure 3.2.4). Thus, as in Experiment 1, pilots enlarged their attentional spotlight (Ericksen & St. James, 1986) to ensure attention allocation to the entire display area. By adapting to shifts in display size, pilots were able to sustain change detection performance with display enlargements, even without a cost to concurrent tasks (Teichner & Mocharnuk, 1979). While adaptation represents the primary mechanism operating in the presented performance findings, it could be argued that surveillance performance was maintained with display enlargement since the stimuli in the periphery were enlarged, making them equally accessible to their smaller counterparts when presented in the small display. While research has indicated that such cortical magnification, which results when stimuli size are enlarged in scale to match the reduction of cortical resolution of the periphery, eliminates the eccentricity effect normally associated with visual search (Carrasco & Frieder, 1996), the degree of enlargement in Experiments 1 and 2 was not equivalent to the degree of scaling used in such studies, suggesting that amplified effort was indeed needed to access peripheral information in the larger display sizes.

Adaptation was also evidenced in the shift of attention allocation from the midrange to the ownship region when the display was enlarged from small to medium. This strategy, which was also found in Experiment 1, evidenced the pilots' need to directly foveate the ownship region in the medium and large displays to gain access to flight control information, which could be accessed peripherally from the midrange region in the small display, given the relatively small visual angle of 0.5° between the inside region of the midrange display region and ownship. As a result, dwells in the midrange region shortened with display enlargement, while dwells in the ownship region lengthened, reflecting the time needed to interpret trends and correct deviations in flight control. Thus, flight control for the altitude and miles-in-trail axes was improved for the medium display relative to the small display, while surveillance also did not suffer.

Though pilots' behavior expressed successful adaptation in surveillance to shifts in display size, two factors limited successful surveillance overall. First, as in Experiment 1, change detection accuracy and response time were both negatively affected by the displacement of events from ownship, which is consistent with literature that has widely documented the negative influence of eccentricity on attention-based tasks (McConkie & Loschky, 2000; Muthard & Wickens, 2004; Podczerwinski et al., 2001; Pringle et al., 2001). Consequently, pilots showed relative neglect to the peripheral region of the display in surveillance, replicating the documented edge effect (Baker, Morris, & Steedman, 1960; Enoch, 1959; Schoonard, Gould, & Miller, 1973), regardless of the size of the display. This finding was also supported by the neglect of the outer display region in attention allocation, when allocation was examined as a function of region area (e.g., a measure of PDT/unit area). It is important to note that while the eccentricity is largely being attributed to effort, the performance degradation associated with distance events may be associated in part to task relevance. While attempts were made to equivalent relevance of an *event*, decoupling *hazard* relevance and hazard location is nearly impossible and unnatural. In fact, the analyses revealed that events, while controlled for relevance, were detected better when they occurred to the side or in front of ownship. Thus, we maintain that the eccentricity effect reported here is due largely in part to effort, but may be confounded slightly by expected hazard relevance (and thus location).

The second factor that limited surveillance resulted from diminishing size, which had a detrimental effect on surveillance in a cluttered display, but not a clean display (see Figure 3.2.2). Thus, while clutter was not a hindrance to pilots in the medium or large displays, pilots were especially sensitive to additional irrelevant information when the display was minified and local density clutter was at its highest level (Kroft & Wickens, 2003). Because clutter did not influence attention allocation as evidenced in the percent dwell time and mean dwell duration data, this difference cannot be attributed to a shift in allocation strategies. Rather, added clutter likely served as a lateral mask of the hazard that changed (Carrasco et al., 1995; Carrasco & Frieder, 1996; Carrasco & Yeshurun, 1998), and the more proximally this irrelevant information was located to the relevant event, which was at its minimum in the small display, the larger the resulting performance decrement (Intriligator & Cavanagh, 2001; Tripathy & Cavanagh, 2002).

In summary, pilots exhibited considerable strategic compensation to display enlargements by widening their scanning patterns in response to the increase in overall display area and directly foveating flight control information in the ownship region when it could no longer be accessed peripherally from the midrange display region. As a result, performance in detecting events did not differ as a function of size, and flight control performance based upon foveation of the central region was improved. While event detection was inhibited for events occurring near the display's periphery, this effect was not amplified with display enlargement. Minifying display size, however, did amplify local density clutter, resulting in poorer change detection in that condition. Thus, the implications of enlarging display size are limited with regards to surveillance, at least up to 36 degrees and when the secondary task is not too difficult as to deplete attentional resources. As was stated for Experiment 1, caution should be taken when extending these findings to a physical display size that induces head movements or to conditions for which resources are highly limited because of difficult concurrent tasks or complex surveillance. We note for example, Recarte and Nunes' (2001) findings that concurrent task load tends to restrict the eccentricity of drivers' scanning.

While the data generated from the first pair of experiments create a consistent and clear picture of the effects of display size on surveillance, the findings from these studies suggest additional research is needed to explicitly examine size effects on distance estimates used in flight control. Experiments 3 and 4 specifically address this issue.

CHAPTER 4: EXPERIMENT 3

Experiment 3 was designed to provide a detailed examination of tracking as a function of display minification within the context of the resolution and urgency models. The data from Experiments 1 and 2 suggest that minifying physical display size influences tracking by limiting display resolution and thus the observer's perception of minute errors and by biasing pilots to estimate deviations as smaller and thus correct them less urgently. Experiment 3 provides a further evaluation of these issues, while also examining the effects of manipulating size through either display minification in a two-dimensional display or axis compression in a three-dimensional display. To evaluate the effect of display size on distance estimates used in tracking, pilots were asked to complete a first order, compensatory tracking task with small or large displays. Size was manipulated by changing the physical size of a 2D display or through axis compression in a 3D display, and these two manipulations to display size were equal in magnitude. In order to investigate how resource limitations might influence the size effects observed in Experiments 1 and 2, pilots were asked to perform single or dual axis control.

Based on the data generated from Experiments 1 and 2 indicating the presence of physical size contamination in tracking and from the review of the literature of biases in flight control with 3D displays, five hypotheses were generated.

1. Display size, regardless of how size was manipulated, is expected to contaminate tracking. As a result, pilots are expected to exhibit greater tracking error and less control activity with a minified display axis.

2. The increase in error can be attributed to a reduction in urgency to the extent that:

    a. the error increase is equal to the display size reduction,

    b. the error increase is *not* equal across different means of display size reduction (physical size minification vs. 3D axis compression), and/or

c. the error increase is different in single and dual task performance, the latter of which can be characterized by resource scarcity.

3. If the degree of size contamination is not equal to the degree of display minification, if the manner in which size is manipulated does not influence the degree of contamination, or if dual axis control does not amplify size effects, than differences in control performance and activity can be attributed to limits in display resolution.

4.1 Methods: Experiment 3

Participants. Participants were 16 aviation students from the University of Illinois, Institute of Aviation, who ranged in age from 18 to 32 years (*M* = 19.9 years). Thirteen participants had their private piloting licenses, while the remaining three participants had student licenses. All participants were right-handed.

Displays. Two-dimensional and three-dimensional displays were used (see Figures 4.1.1 and 4.1.2). The 2D display depicted a vertical and a horizontal axis in two separate panels that were separated by 17 degrees of visual angle (19 cm). The vertical axis was always represented in the left panel, while the horizontal axis was always shown in the right panel. On half of the trials in which the 2D display was used, the vertical (left) panel was presented in a large scale, while the horizontal (right) panel was presented in a small scale. On the remaining half of trials, this was reversed. The cross in the center of each panel represented the target location for each axis. As mentioned above, the sizes of the scales were varied to be small (about 2 degrees of visual angle or 2 cm) or large (about 4 degrees of visual angle or 4 cm). A scale, presented in the lower left-hand corner of each panel, and tick marks, shown along the edges of each panel, were used to denote distance from the target point within each display panel. Distance on the screen was depicted as pixels, but representative of meters in the world (i.e., world units). The same control displacement of the stick would produce an identical response *in world units* between the two displays and thus a slower response in pixel movement on the smaller display.

The 3D display depicted both the horizontal and depth axes in a single, integrated panel. Lines, which converged with increasing distance, were added to further convey the sense of display depth. As was the case in the 2D display, a cross was located in the center of the panel to represent the target location for the axes and a scale and tick marks were included to denote distance from the target location. Size was not explicitly manipulated, though the depth axis was the same size as the small axis in the 2D display (about 2 degrees of visual angle or 2 cm), due to the compression associated with representing depth in only two dimensions. The horizontal axis was the same size as the large display in the 2D display, as this axis was not compressed. Thus, the degree of axis compression in the 3D display was equal to the degree of size reduction in the 2D display.

Task. Participants completed a first-order, single or dual-axis compensatory control task using the 2D or 3D display. Participants were asked to keep the icon, representing the pilot's ownship, within 500 meters of the target location at all times (i.e., the same criterion for both axes world units). The disturbance was a quasi-random sum of three nonharmonically related sine waves with a bandwidth of 0.5 Hz, and participants were told that the icon would move randomly in all possible directions. When using the 2D display, participants were asked to control either the vertical axis alone, the horizontal axis alone, or the two axes simultaneously. In the 2D display, control was accomplished through the use of two joysticks. The vertical axis, which was depicted in the left panel, was controlled with the left hand through the left joystick. The horizontal axis, conversely, was controlled with the right hand and the right joystick. When both axes were controlled simultaneously, both joysticks were used.

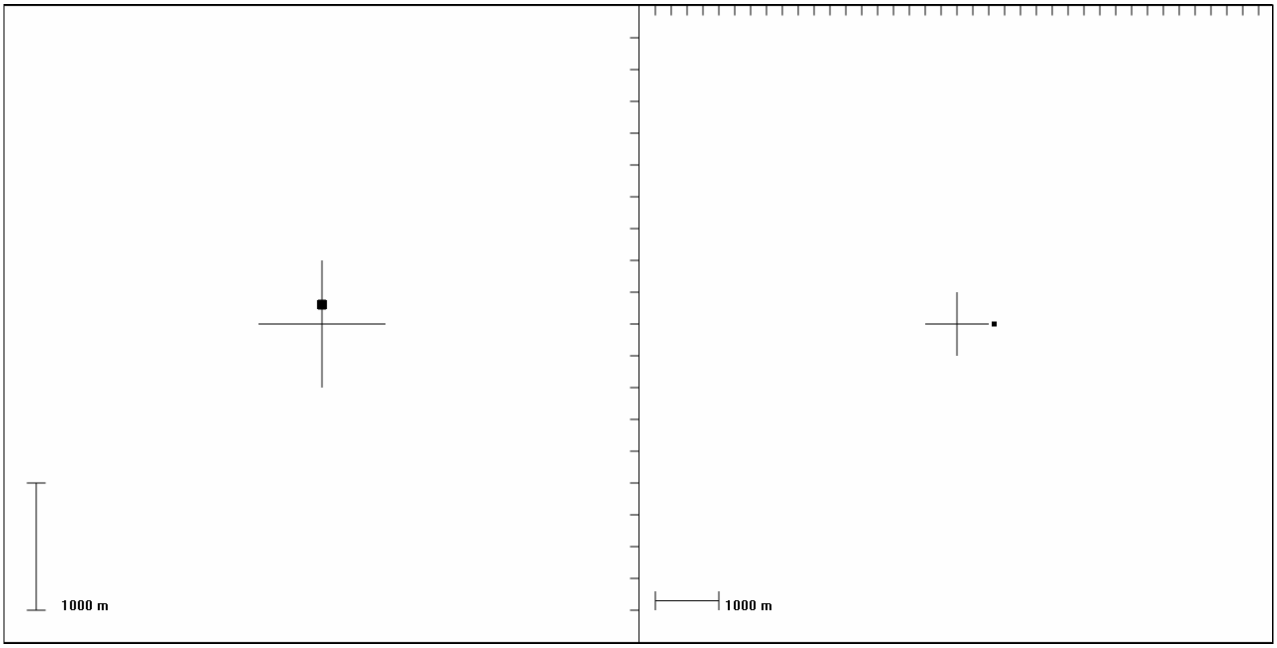


Figure 4.1.1. Two-dimensional display with the vertical axis in left panel and horizontal axis in right panel. For this particular trial, the vertical axis presented in a large scale and the horizontal axis was presented in a small scale, though size was counterbalanced across axes in the experiment.

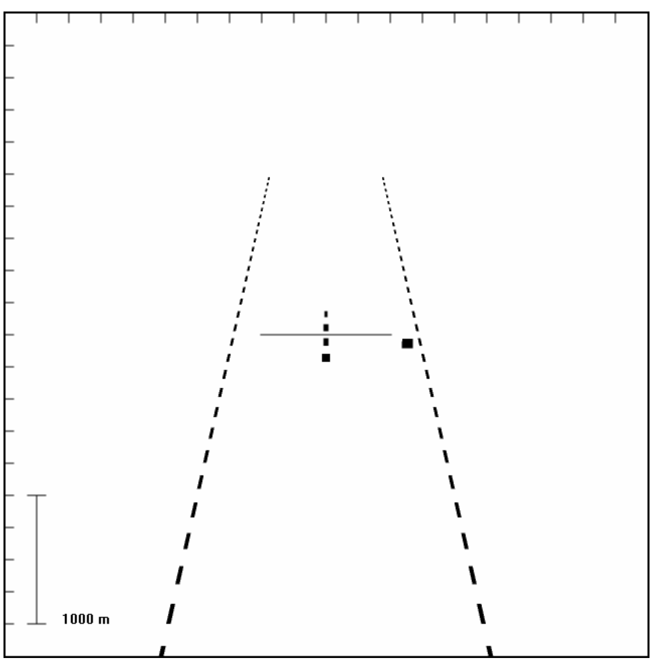


Figure 4.1.2. Three-dimensional display.

When using the 3D display, participants were asked to control the depth axis alone, the horizontal axis alone, or the two axes simultaneously. The right joystick, manipulated with the right hand, was always used to control both axes, and forward movement was used to compensate for a downward error, as if propelling the vehicle forward in the perspective of the 3D space. An integrated control format was chosen for the integrated 3D display and separate controls were chosen for the 2D display in order to maximize display-control compatibility within each display type (Fracker & Wickens, 1989). Participants completed a practice trial with both the 2D and 3D display and nine experimental trials, each of which lasted two minutes. The entire experimental session lasted thirty minutes.

Table 4.1.1. Table of conditions for the 2D physical size manipulation. Participants completed one trial for each of the six conditions listed in the bottom row of the table, totaling six trials for the 2D Physical Size manipulation. Three additional trials were also done with the 3D axis compression manipulation, as detailed in Table 4.1.2.

2D Physical Size Manipulation					
Single				Dual	
Small		Large			
Vertical (L)	Horizontal (R)	Vertical (L)	Horizontal (R)	Large Vertical (L) and Small Horizontal (R)	Small Vertical (L) and Large Horizontal (R)

Table 4.1.2. Table of conditions for the 3D axis compression manipulation. Participants completed one trial for each of the three conditions listed in the bottom row of the table, totaling three trials for the 2D Physical Size manipulation. Six additional trials were also done with the 2D physical size manipulation, as detailed in Table 4.1.1.

3D Axis Compression Manipulation		
Single		Dual
Compressed Depth	Noncompressed Lateral	Compressed Depth and Noncompressed Lateral

Experimental Design. Display dimensionality, axis size, and task load were manipulated in a within-subjects design. Tables 4.1.1 and 4.1.2 detail these manipulations for 2D physical size and 3D axis compression, respectively. As shown in Table 4.1.1, for the 2D physical size manipulation, task load, axis size, axis direction were varied to produce 6 experimental conditions. Specifically, participants could control either the horizontal or vertical axis alone in the single-task condition, and the sizes of these axes could be presented as small or large. In the dual task condition, the horizontal and vertical axes were always controlled simultaneously, and one of the two axes was presented in a small scale, while the other was presented in a large scale. Within the 2D physical size manipulation, the vertical axis was always presented in the left panel and controlled with the left hand, while the horizontal axis was always presented in the right panel and controlled with the right hand.

For the 3D axis compression manipulation (see Table 4.1.2), axis size and task load were varied to produce three experimental conditions. Thus, participants could control the compressed depth axis alone, the noncompressed lateral axis alone, or both axes simultaneously. Unlike the 2D physical size manipulation, axis direction was always matched with axis size, such that the depth axis was always compressed and the lateral axis was always noncompressed. With the 3D display, both axes were presented in a single integrated panel, and control of both axes was always performed with the right hand. Trials were blocked and counterbalanced across participants by display dimensionality and task load, while control axis and display size were randomized.

Dependent variables included root mean square (RMS) error and RMS control velocity, the latter measuring control effort. Each participant performed one trial within with each of the nine display conditions.

4.2 Results: Experiment 3

Tracking error, plotted as a function of display size and dimensionality and collapsed over single and dual axis tracking, is shown in Figure 4.2.1. The predicted error differences under the pure normative hypothesis and the pure urgency hypothesis are also depicted within the figure. Figure 4.2.2 presents the same data as Figure 4.2.1, but does so for control activity. The full data set for Experiment 3 is shown in Table 4.1.1.

As shown in Figure 4.2.1, when the ratio of display units to world units was reduced, either by minifying the physical size of the 2D display or through axis compression in the 3D display, control error increased by 8% and 27%, respectively ($F(1, 15) = 30.7$, $p < 0.001$; $F(1, 15) = 39.0$, $p < 0.001$, respectively). These findings were mirrored in analyses for control activity (6.8% reduction, $F(1, 15) = 22.7$, $p < 0.001$ for 2D physical size; 33.6% reduction, $F(1, 15) = 67.8$, $p < 0.001$ for 3D axis compression), which are plotted in Figure 4.2.2. Table 4.2.2 summarizes the degree of performance reduction and control reduction relative to the degree of display minification. These data suggest that size did then, at least to some degree, contaminate the distance (error) estimates implicitly used in tracking. Because these findings cannot be explained within the constraints of the normative model, the analysis now turns to examining the contributing roles of resolution and urgency.

Recall that the resolution model posits that the smallest deviations portrayed on the small display will be too minute to be noticed and thus will go uncorrected. Because the postulates of this model rely only upon the perceptual differences between the small and large displays and not in the manner in which those differences are created, the decrement associated with display minification should not differ as a function of how size was manipulated. This premise was invalidated by the significant Dimensionality X Size interaction ($F(1, 15) = 9.8$, $p = 0.007$), which indicated that a size reduction due to 3D axis compression created a greater increase in error than a reduction of the same magnitude in the minification of the physical size of the 2D display. Thus, the data suggested that effort investment for the larger axis was amplified when the enlargement was accomplished by compressing the axis of a 3D display relative to when it was accomplished by increasing the physical size of a 2D display. This difference was again reflected in the significant interaction between dimensionality and size in control activity ($F(1, 15) = 41.9$, $p < 0.001$), with a larger effect of size for the 3D than for the 2D display (see Figure

4.2.2). These findings bolster the presence of urgency in tracking by suggesting an influence of display format on resource allocation strategies.

It should also be noted that a significant main effect of dimensionality was also found for tracking error ($F(1, 15) = 23.5$, $p < 0.001$), indicating that control performance was poorer for the 2D display than for the 3D presentation. It is hypothesized that this difference reflects the cost of visual scanning between the two separate panels of the 2D display. This cost was anticipated (Fracker & Wickens, 1989) and is not of particular theoretical interest here.

To the extent that urgency is indeed operating and that effort allocation is resource limited, it would be expected that the effect for display size should be amplified in dual axis tracking when resources are at a premium. Surprisingly, this premise of the urgency hypothesis was not confirmed. While task load, manipulated as single versus dual axis control, significantly reduced control performance for the 2D display only ($F(1, 15) = 80.7$, $p < 0.001$), reflecting the above mentioned cost of scanning, this variable did not interact with size ($p > 0.10$). Thus, resource limitations in the dual axis condition, which should be present to the extent that urgency was operating, were not found. These data provide support for some influence of the perceptually-based resolution mechanism, which does not heed the role of resource allocation or resource scarcity in tracking.

Finally, an extreme view of the urgency hypothesis posits that pilots should exhibit twice the error and half the control activity when the display was reduced to half of its initial size. While the data indicated that display size did significantly contaminate deviation distance judgments as evidenced in the differences in tracking error and the effect sizes for the findings were large, the magnitude of the differences between the means was much smaller than that predicted by the pure urgency model. Specifically, enlarging the display by 200% produced an average reduction in tracking error of only 14% and an average increase in control activity of 27%. These differences can be seen by comparing the slope of the predicted urgency results to that of the actual data for the 2D and 3D displays in Figures 4.2.1 and 4.2.2.

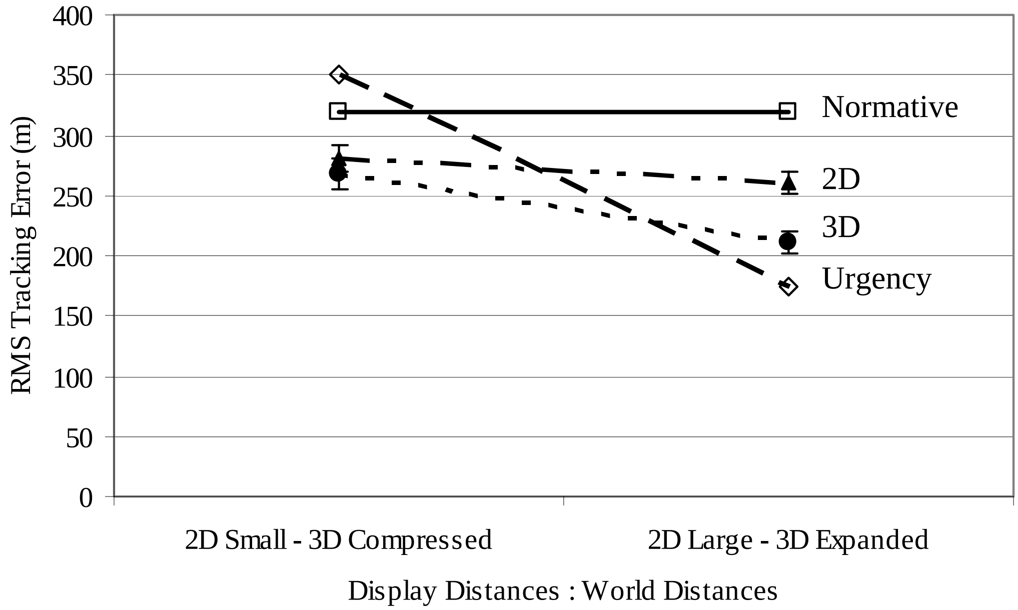


Figure 4.2.1. Tracking error for the 2D and 3D displays presented as a function of display size. The predictions for the urgency and normative models are also plotted.

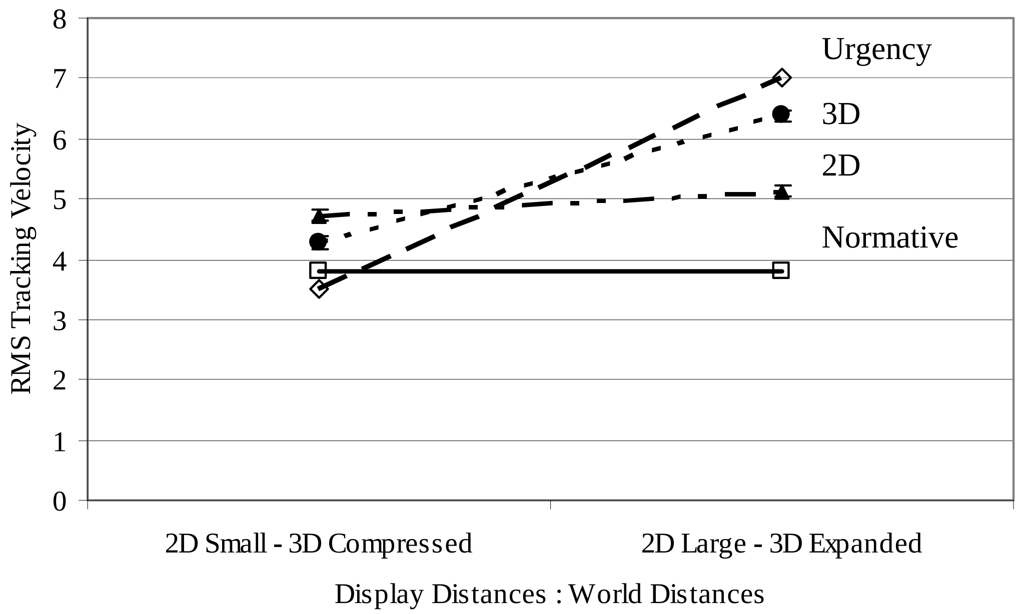


Figure 4.2.2. Control activity for the 2D and 3D displays presented as a function of display size. The predictions for the urgency and normative models are also plotted.

Table 4.2.1. Detailed descriptive analyses for the two axes of flight as a function of display size and dimensionality for Experiment 3. The *Comparisons* column describes the significant display size findings. Cells denoted as *NS* represent nonsignfiicant findings. Note that in all cases, display minification led to greater RMS error and lowered stick activity.

Measure	Dimension	Axis Load	Statistic	Small	Large	Comparisons
RMS Error	2D	Single	Mean	216.1	201.2	S > L
			SE	8.3	8.6	
		Dual	Mean	345.3	320.4	S > L
			SE	15.0	14.2	
		Axis Load Comparisons		Dual > Single	Dual > Single	
	3D	Single	Mean	269.1	211.4	S > L
			SE	18.4	8.6	
		Dual	Mean	267.1	210.7	S > L
			SE	14.6	11.6	
		Axis Load Comparisons		NS	NS	
Control Activity	2D	Single	Mean	5.4	5.6	L > S
			SE	0.6	0.5	
		Dual	Mean	4.1	4.6	L > S
			SE	0.4	0.4	
		Axis Load Comparisons		Dual > Single	Dual > Single	
	3D	Single	Mean	5.0	6.7	L > S
			SE	0.6	0.8	
		Dual	Mean	3.5	6.1	L > S
			SE	0.5	0.7	
		Axis Load Comparisons		NS	NS	

Table 4.2.2. Table details the degree of display reduction when the display was reduced from large to small in Experiment 3. Correspondingly, the degree of performance reduction and reduction in stick activity is also shown. Nonsignificant findings are indicated by "NS." Performance and activity were reduced, especially for the 3D display, but not to the extent that display size was reduced.

Dimensionality	Reduction	Large to Small
2D Display	Display Reduction	50 %
	Performance Reduction	7.6 %
	Activity Reduction	6.8 %
3D Display	Display Reduction	50 %
	Performance Reduction	27.0 %
	Activity Reduction	33.6 %

4.3 Discussion: Experiment 3

Experiment 3 examined the influence of display size, manipulated through changes to the physical size of a 2D display and through axis compression in a 3D display, on tracking within the context of the normative, resolution, and urgency models. Consistent with findings from the first pair of experiments and with past research (Abbott & Moen, 1981; Wickens et al., 1996), the results indicated that flight control became poorer with both a reduction in the physical size of the display and through axis compression.

Furthermore, evidence suggested that the manner in which size was manipulated had a direct influence on tracking performance and control activity, thus supporting the influential effect of urgency in flight control. Specifically, participants' tracking behavior expressed less urgency in correcting deviations in small displays, particularly when minification was accomplished through axis compression in the 3D display. These data are consistent with the work of Wickens et al. (1996), who suggested that pilots show larger error when tracking a compressed axis on a 3D aviation display because they underestimate distances along this axis.

Though this finding directly bolsters the feasibility of the urgency model, the reduction in error and increase in control activity found with larger displays were small (14.0 %) relative to the degree of display enlargement (i.e., doubled, predicting a 50% decrease in error reduction). Thus, the effects for urgency were minor, though larger in the 3D (21.3%) than in the 2D display (7.1%), as detailed in Table 4.2.2. Because urgency is associated with effort and resource-driven processes, any size effect that results from differences in urgency might be expected to be amplified when these resources are heavily tapped, as in the dual axis control condition. This interaction was not found, however, providing support for the conclusion that urgency played only a moderate role in manual control and that the rest of the effect can be attributed to resolution. It is important to note, however, that the dual task manipulation may not have provided a sensitive form of imposing task load. While a main effect of task load was found, the effect was only present in the 2D display where the two axes were presented in separate panels, suggesting that the decrement may have been due to scanning costs, rather than to a limitation in available perceptual-cognitive or motor resources. In particular, such scanning costs in the 2D display did not appear to have been influenced by axis size, with the larger axis receiving more visual attention. Had this been the case, the size effect with the 2D display panels should have been evident only in dual axis conditions, but in fact it was equally present in both single and dual axis conditions.

Thus, while analyses revealed that perceived urgency in correcting path deviations serves as a driving factor for the performance decrements that result with display minification, the presented analyses thus far have only focused on overall tracking performance and control activity as a function of display size, rather than examining control as a function of *deviation size.* Because one of the key tenets of the resolution model is that control is hindered for display minification for the *smallest deviations* (or smallest rates of deviation)*,* an examination of control activity as a function of deviation size is essential to conduct a thorough evaluation of this model.

Furthermore, the analyses of flight control and tracking from the first three experiments suggests that the implicit distance (deviation) estimates used to drive corrective control in tracking are influenced by display scale. Thus, the final experiment examines the extent to which these biased estimates translate to other tasks that are reliant upon implicit distance estimates, namely time estimation and risk assessments used in route selection.

CHAPTER 5: EXPERIMENT 4

Experiment 4 provides an overarching assessment of the effects of display size on pure distance estimation, as well as on estimates used in the tasks of flight control, time estimation, and risk assessment and route selection. In this final experiment, pilots were asked to select and fly along two flight routes, while considering the risk posed by terrain, weather, and traffic aircraft. Periodically throughout each trial, pilots were also asked to make distance and time estimates. Hazard and flight path information was presented on an integrated hazard display, which was equipped with a primary flight display panel. In a manner identical to Experiment 3, the size of these displays was manipulated by changing the physical size of the 2D display and through axis compression in the 3D display.

Consistent with the findings from the three previous experiments, two hypotheses for flight control were generated.

1. Display minification, regardless of how display size was manipulated, is expected to produce a decrement to flight control performance and a reduction in flight control activity.

2. Based on the findings from Experiment 3, however, 3D axis compression is expected to cause a greater display size decrement than minifying physical display size, a difference which would be attributed to the role of urgency in flight control.

If size contamination were to be found in probed estimation responses, it is expected that time estimation would be contaminated as a function of display size to a greater degree than distance estimation. This would result because time estimation is more cognitively demanding than simple distance estimation and thus is more sensitive to biasing and attribute substitution.

As was described briefly in the Introduction, pilots were tasked with balancing safety and efficiency while selecting one of two presented flight paths to travel, namely a shorter but riskier route and a route that diverted around hazards but was less efficient. While no research was found that examined risk assessments used in route selection as a function of display size, several hypotheses can be generated to explain the predicted outcomes.

1. To the extent that display size contaminates decision making, pilots should rate the risk of the flight paths as higher when using the smaller display, as the distance between the route and impending hazards will be seen as smaller. This would result from the ease with which display distance information could be accessed.

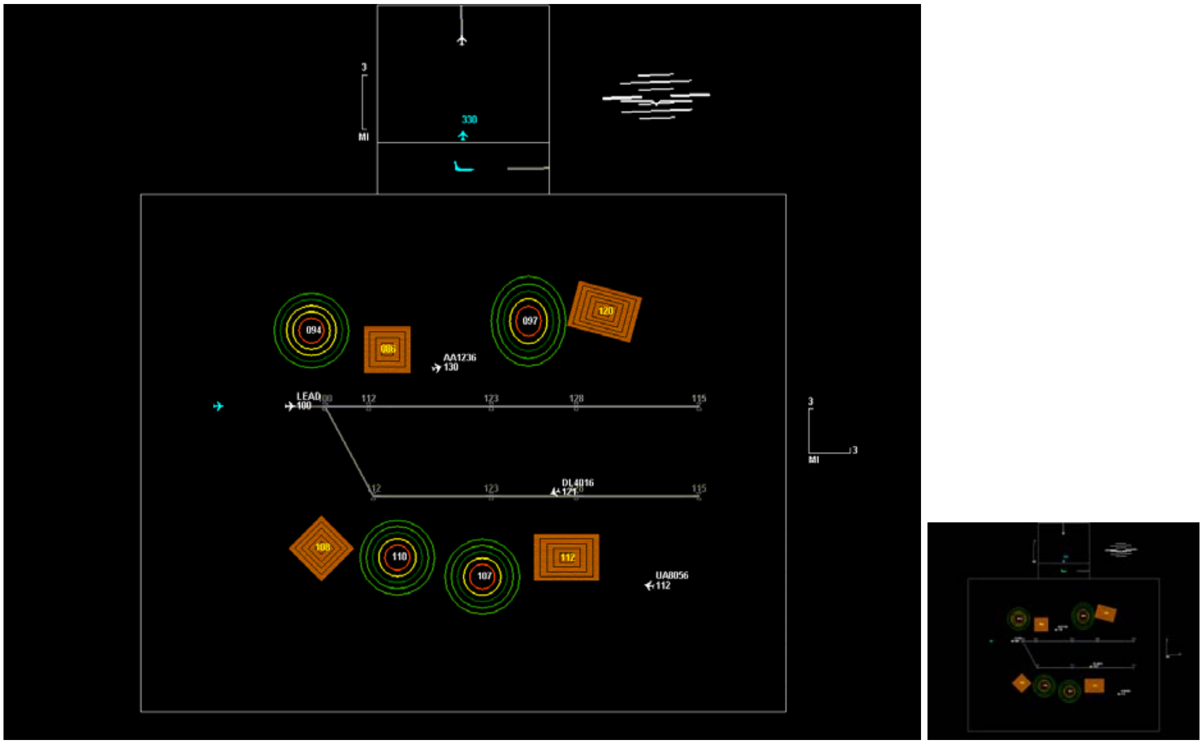
2. To the extent that size contaminates risk assessments, these biased estimates could translate into contaminated route choices. As a result, a pilot who has chosen a safer but less efficient route when presented on a small display would choose a less safe, but more efficient route when presented on a large display.

3. Given that size effects have been found to be more pronounced when size is manipulated through axis compression than through changes to the physical size of a display, size contamination in route selection is expected to occur more frequently in the 3D display than in the 2D display.

5.1 Methods: Experiment 4

Participants. Sixteen student pilots from the University of Illinois, Institute of Aviation volunteered to participate in the present experiment. Twelve pilots were male, while the remaining four were female. Participants had an average of 129.9 flight hours of experience. Six of the pilots were instrument certified, while the remaining ten pilots were undergoing instrument certification at the time of the experiment.

Displays. The presented display consisted of two separate panels, namely the integrated hazard display and a primary flight display presenting the three axes of flight. These panels are shown in Figure 5.1.1. The integrated hazard display depicted traffic, weather, and terrain information in a single panel. Traffic and weather were represented using the icons and data tags described in Experiments 1a and 1b, while the terrain was depicted with topographical terrain pieces. For the terrain, the altitude of the peak was represented as a three digit data tag, in a manner identical to the altitude representation used for traffic and weather.



(a) (b)

Figure 5.1.1. (a) Large two-dimensional integrated hazard display. (b) Small two-dimensional integrated hazard display.

In addition to the described airspace hazards, two flight paths were shown on the integrated hazard panel to evaluate size-induced preference reversals. The short path was always a straight and efficient path traveling in a north-bound or east-bound direction. The diversion flight path always deviated thirty seconds after the start of the trial and then continued in a direction parallel to the short, more efficient flight path. Waypoints were located along each of the flight paths and were designated by small bowtie symbols. Above each waypoint was a three digit code, which identified the altitude of the commanded flight path at that waypoint. The pilot's ownship, which was presented in blue, and a lead aircraft, which was located five miles directly in front of ownship, were also depicted on the integrated hazard display.

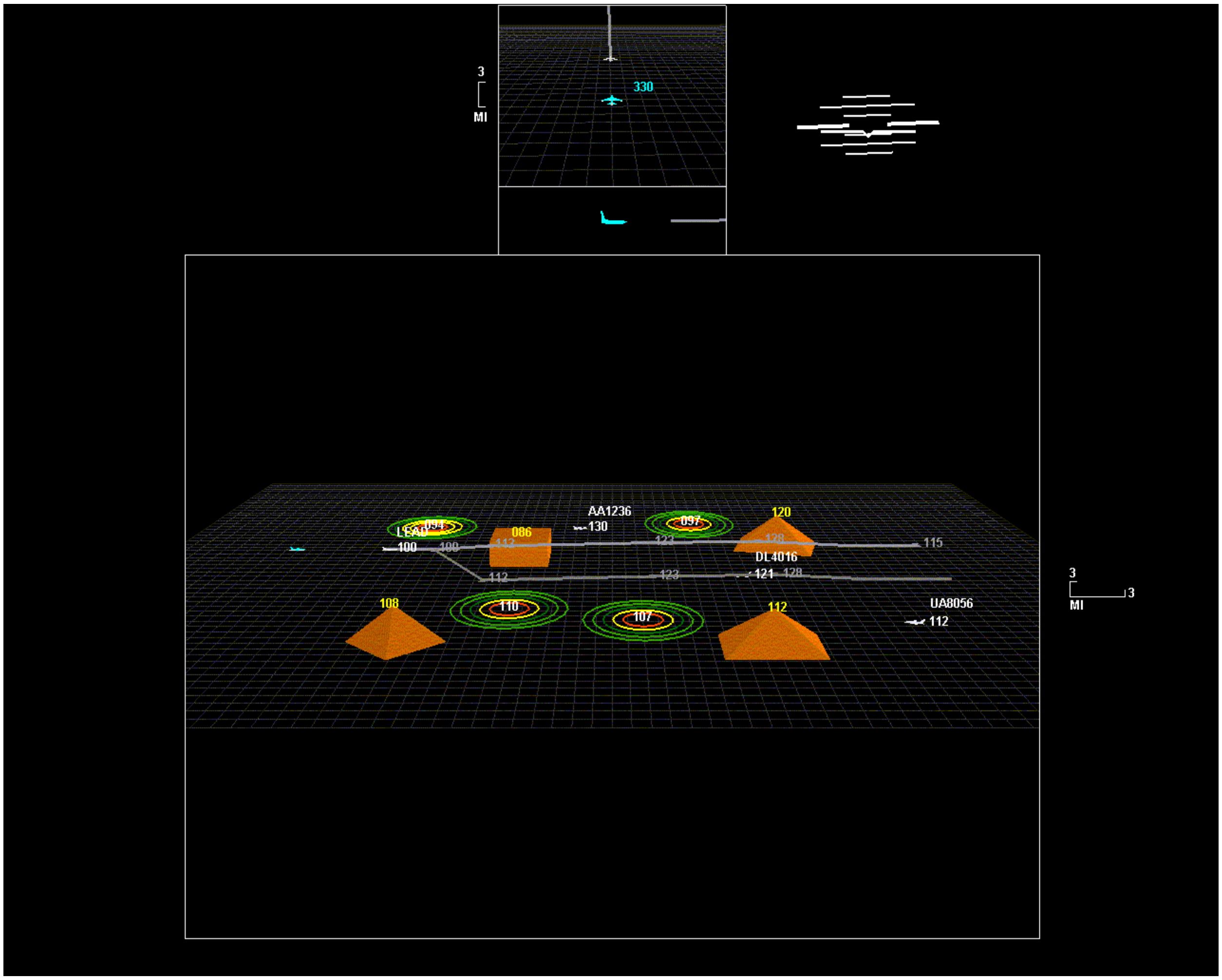


Figure 5.1.2. Three-dimensional integrated hazard display.

The primary flight display was centered above the integrated hazard display panel. This flight display depicted a zoomed-in view of ownship, the lead aircraft, and the selected flight plan. The pilot's airspeed was depicted in a three digit data tag located directly to the right of ownship. This information was shown as a top-down view in the upper panel of the primary flight display, while the lower panel depicted a side-view. The primary flight display was oriented as track-up and the location of the lead aircraft and the flight plan moved relative to ownship. Directly to the right of the primary flight display panel was an attitude directional indicator, which depicted the bank and pitch of the aircraft.

The size of the integrated hazard display and primary flight display panels were manipulated in two manners, namely through changes to their two-dimensional physical size or through axis compression in a three-dimensional display. The two sizes of the two-dimensional display are depicted in Figure 5.1.1. Figure 5.1.2 shows the display in a three-dimensional form. Note that the dimensionality of the integrated hazard display was always mirrored in the dimensionality of the primary flight display.

Physical size was manipulated for the two-dimensional condition by presenting participants with a small and large display. Within the small condition, the integrated hazard display measured 8 by 6 cm (10° by 7°) and the primary flight display encompassed 2.4 by 2.5 cm (3° by 3°). With the large display, the integrated hazard display panel measured 29 by 22 cm (36° by 27°), while the primary flight display measured 7.4 by 7.6 cm (9° by 9°). Thus, the dimensions of the large display were reduced by 72.2% to produce the small display. With all changes in display size, the text and icon size of all information present on the display also changed proportionately.

Size was manipulated in the 3D display by compressing the axis along the line of sight. Thus, the axis parallel to the line of sight represented the "small" axis, while the non-compressed axis orthogonal to the line of sight represented the "large" axis. The extent of the compression was defined such that the compressed axis in the three-dimensional display (longitudinal or miles-in-trail) was equal in display length to the small presentation of this axis in the two-dimensional display (e.g., both had a three to one ratio). Conversely, the non-compressed axis (vertical and lateral control) in the three-dimensional display was equal in display length to the large presentation of this axis in the two-dimensional display.

Tasks. During the trials, the participants were responsible for three main tasks: flight control, flight plan selection, and making distance and time estimates. In the first task, pilots were instructed to fly ownship along the flight path. Pilots' target altitude and heading were defined by the waypoints along the presented routes. In addition to maintaining the lateral and vertical perimeters defined by the flight plan, pilots were also instructed to maintain a five mile separation from the lead aircraft by increasing or decreasing their own airspeed. While general deviation information could be obtained from the integrated hazard display, pilots were specifically instructed to use only the primary flight display for error correction in the flight control task. The upper panel of the primary flight display provided heading and miles-in-trail deviation information, while the lower panel of the display provided deviation information for the vertical axis of flight. Because the primary flight display was always oriented as track-up, the miles-in-trail axis was always compressed when the three-dimensional display presentation was used.

A scale was presented to the left of the primary flight display to assist in miles-in-trail distance judgment, and an attitude directional indicator, located to the right of the primary flight display, was presented to provide pitch and roll information. While all flight maneuvers were made with a joystick, airspeed could be manipulated by pressing keys located on the joystick handle, which produced a constant increase or decrease of speed at 1 knot per button press. Holding in the throttle button would also cause the aircraft's airspeed to increase or decrease at about 10 knots per second. Disturbances to flight control were introduced along all the heading and vertical axes of flight at a bandwidth of 0.05 Hz. For the miles-in-trail axis, the speed of the lead aircraft was varied randomly every 45 to 90 s by at least 50 knots. The implemented change in the lead aircraft speed was gradual and changed at a rate of 100 knots per minute until it reached the commanded speed.

In the flight planning task, pilots were asked to select one of the two presented flight paths within thirty seconds from the start of the trial. Pilots were instructed to select flight plans on the basis of efficiency, to the extent that flight safety was not compromised. Pilots were informed that, for the purpose of the experiment, flight safety was defined as the projected distance between the pilot's own aircraft and each of the hazards in the airspace. To select a flight plan, pilots used a mouse to input the flight plan choice. After selecting a route, pilots were asked to rate the overall safety of *both* of the routes, using a Likert scale ranging from 1 ("very unsafe") to 7 ("very safe"). Finally, pilots rated their confidence in the overall judgment using a Likert scale similar to the one just described, where judgments could range from 1 ("very unconfident") to 7 ("very confident").

In the final task, pilots were asked to make distance and time judgments periodically throughout the trial. These judgments, which occurred in response to the question probe that appeared in the upper right hand corner of the display, were made every thirty seconds and occurred ten times in each trial. Half of these probes were designed to require estimations of distance (e.g., "How far is AA612 from the mountain at 12,000 ft?"), while the remaining half were designed to induce time estimates (e.g., "How long until AA612 reaches the perimeter of the mountain at 12,000 ft?"). Questions were designed such that estimates were made along the north-south axis, as well as the east-west axis in the two-dimensional display. Consequently, when the information was presented in the three-dimensional display, these estimates were made along the depth axis or the lateral axis, allowing for an analysis of compression effects on both distance and time estimates. All responses were open-ended and were entered with a standard keyboard. Distance responses were given in miles, while time responses were given in seconds. A scale was provided to the right of the integrated hazard panel to assist in making the distance judgments. Participants completed one practice trial and eighteen experimental trials. Each trial lasted about five minutes, and the experimental session took about two hours.

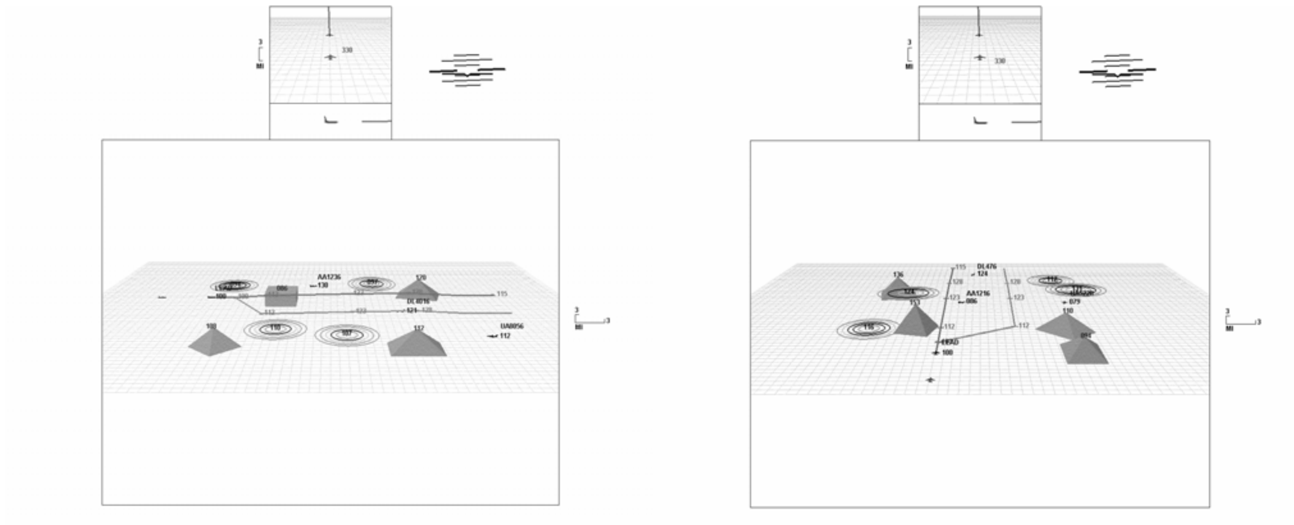
Risk Algorithm. Computational algorithms were designed to assess and weight both the safety and efficiency of the two presented routes. Risk was measured as the distance from ownship to the hazard at the point of closest passage and was equivalent to the parameter of safety described to participants during the instructional phase of the experiment (see Appendices D and E). These risk values were aggregated for all of the hazards with respect to each flight path including those hazards that were not close to the path at the moment the risk was assessed, but could be moving on a converging path with ownship's future flight location. Efficiency was measured as the amount of time needed to traverse the airspace on each flight path. Both efficiency and risk were weighted, with risk receiving a weight twice that of efficiency because of its greater importance to flight, and then summed to produce a final path value. The value produced by the algorithm was not used as a measure of correctness in flight path selection. Rather, this value was used in trial construction as a form of measuring the balance of safety and efficiency for each of the presented flight paths. As such, several combinations of safety and efficiency could be achieved and quantitatively defined, each of which are described in the Flight Plans section.

Flight Plans. The differential risk of the two presented flight plans was manipulated to produce variations in plan selection difficulty. Recall that the two flight plans differed in efficiency. In the easiest plan selection condition (*Safe*), the more efficient route was also significantly safer than the long route. In the difficult condition (*Risky*), the shorter route was somewhat less safe than the longer route. Thus, the pilot would need to balance the need for safety and efficiency in making his decision. In the final condition (*Very Risky*), the shorter route was significantly less safe than the longer route and a pilot taking this route would be exhibiting risky behavior and sacrificing flight safety. Pilots were not told about the 2:1 weighting of safety and efficiency in route selection as dictated by the risk algorithms described above. Although not providing pilots with this information may have affected the *overall* preference for efficient versus safe routes, it should not have affected the *modulation* of this preference by size, which tests the fundamental hypotheses of the experiment. Additionally, while the weighting of safety and efficiency as defined by the constraints of the algorithm may be slightly artificial in its representation of pilots' actual subjective weightings, it is nonetheless qualitatively representative of the importance of safety in flight at the expense of efficiency, even if the algorithmic and subjective weightings are not quantitatively equivalent. The quantitative values, obtained using the risk algorithm described above, for each of these flight path conditions is shown in Table 5.1.1. Note that the risk of the efficient path increased linearly with each condition.

Table 5.1.1. Quantitative values of risk for the efficient and diversion routes in each of the three flight plan conditions. Values were determined using risk algorithm described in Risk Algorithm section.

Flight Plan Condition	Efficient Route Risk	Diversion Route Risk
Safe	30	45
Unsafe	45	30
Very Unsafe	60	30

Experimental Design. Path direction, flight plan safety condition, display dimensionality, and display size were manipulated in a within-subjects design. Display size was manipulated in two manners. For the two-dimensional display presentation, physical size was manipulated to produce small and large displays. For the three-dimensional display presentation, size was manipulated through axis compression, where the axis parallel to the line of sight represented the small display scale and the axis orthogonal to the line of sight represented the large display scale. In order to produce size changes within the three-dimensional navigation integrated hazard display, the direction of the paths was manipulated. As such, the paths could travel along the compressed depth display axis, thus requiring distance estimates from hazards along the large uncompressed lateral axis, or they could travel along the large uncompressed lateral display axis, thus requiring distance estimates from hazards along the small compressed depth axis. Panel (a) of Figure 5.1.3 shows the flight paths traveling along the large, noncompressed axis, while panel (b) depicts the path along the small compressed axis. This path direction manipulation was thereby mirrored in the two-dimensional displays, by varying path direction as traveling west to east or south to north. Of course, in the 2D display there was no difference in compression across those two display axis directions.



(a) (b)

Figure 5.1.3. (a) Paths traveling along noncompressed axis, while distance estimates were made along the compressed axis. (b) Paths traveling along compressed axis, while distance estimates were made along the noncompressed axis

For the task of tracking, within the 3D primary flight display, the effect of axis compression was totally confounded with axis of control. The degree of compression effect here, however, can be inferred by comparing performance differences across flight control axis within the 3D display to that within the 2D display where axis compression was not present. This analysis will be performed and discussed further within the Results section.

Plan selection dependent variables included plan selection response time, subjective path risk, and subjective confidence. For the estimation tasks, both probe response time and RMS error measures were collected. Flight control measures included altitude root mean square (RMS) error, heading RMS error, and the mean absolute error in tracking the distance from ownship to the lead aircraft.

5.2 Results: Experiment 4

Flight Control. Flight control was assessed as a function of flight axis and display size, both for physical size manipulations of the 2D display and for axis compression in the 3D display. Figure 5.2.1 plots flight control error for the three axes of flight as a function of display size when the physical size of the 2D display was manipulated. As shown in this figure, a decrement was found in flight control performance with display minification for all axes of flight ($F(1, 15) = 22.0$, $p < 0.001$). Display size and the axis of flight control did not interact ($p > 0.10$), suggesting that the ratio of decrement that occurred as a function of display minification was equivalent across the three axes of flight. Across all three axes, the average decrement in performance associated with display minification reached only an average of 41%, which was again, as in Experiment 3, less than the reduction of display size in Experiment 4 (72%).

In the 3D display, axis compression for the miles-in-trail depth axis was also associated with poorer flight control performance than the uncompressed lateral and vertical axes ($F(1, 15) = 191.2$, $p < 0.001$). Because this difference is confounded by the difference in lateral and vertical tracking versus miles-in-trail tracking (as seen with the 2D display), the effect of axis compression on flight control was further evaluated by comparing the ratio of error from lateral and vertical tracking to miles-in-trail tracking in the 3D display with the effect of axis in the 2D display than in the 2D display, at least a portion of the effect could be attributed to axis compression. This analysis revealed that the increase in error when comparing the averaged lateral and vertical axes to the miles-in-trail axis was 33% greater ($F(2, 30) = 3.8$, $p = 0.03$) in the 3D display condition than in the 2D display condition. Thus, the *added* increase in error can be attributed to the fact that the miles-in-trail axis was compressed in the 3D display, relative to the 2D display in which it was fully expanded.

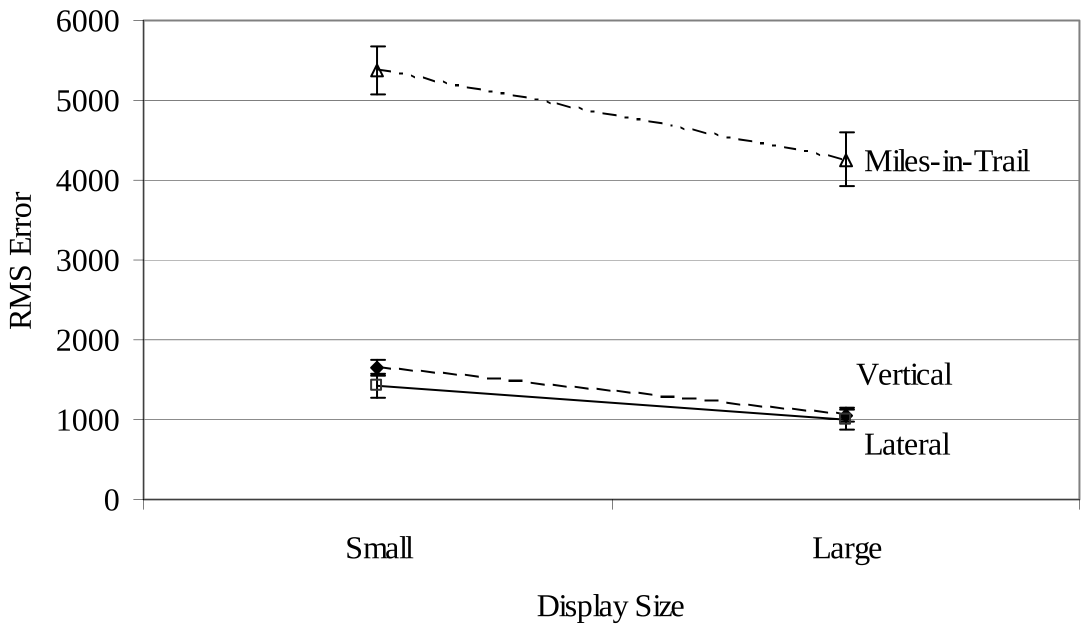


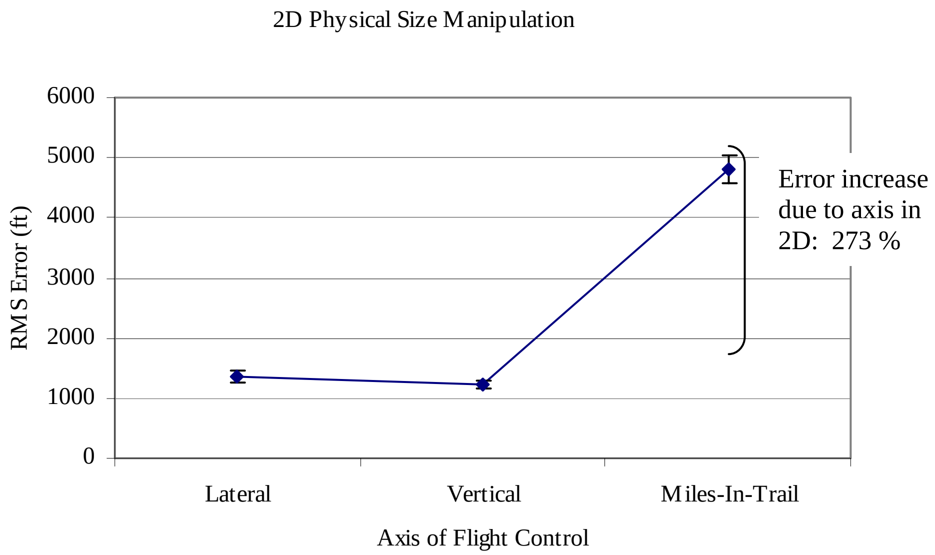
Figure 5.2.1. RMS Error plotted for the three axes of flight as a function of display size. Note that tracking error, perceived from the upper display panel of Figure 5.1.3, was reduced with display enlargement for all three axes.

A subsequent analysis was conducted to determine whether the degree of size contamination found in flight control was greater for the 3D display than for the 2D display, as was found in Experiment 3. To make this comparison, the amount of size contamination in the 3D display was determined after controlling for the confounding decrement associated with tracking the miles-in-trail axis relative to the vertical and lateral axes. Figure 5.2.2 shows the degree of decrement associated with tracking the miles-in-trail axis, relative to the averaged lateral and vertical axes, as a function of dimensionality. The graphed values for 2D physical size manipulation have been collapsed across the small and large displays. As shown in the figure, the degree of decrement miles-in-trail decrement for the 2D display was 273%, while the decrement in the 3D display reached 431%. As the axis of flight control was not confounded with display size in the 2D display, the magnitude of performance reduction in this display is representative of the increased difficulty of tracking the miles-in-trail axis independent of display size. Thus, the remaining 158% (431% less the 273% associated with control axis) of decrement found in the 3D display can be attributed to axis compression. As this size decrement is considerably greater than that associated with display minification in the 2D display (41%), we can conclude that flight control was worsened when minification was accomplished through 3D axis compression relative to 2D physical size minification.

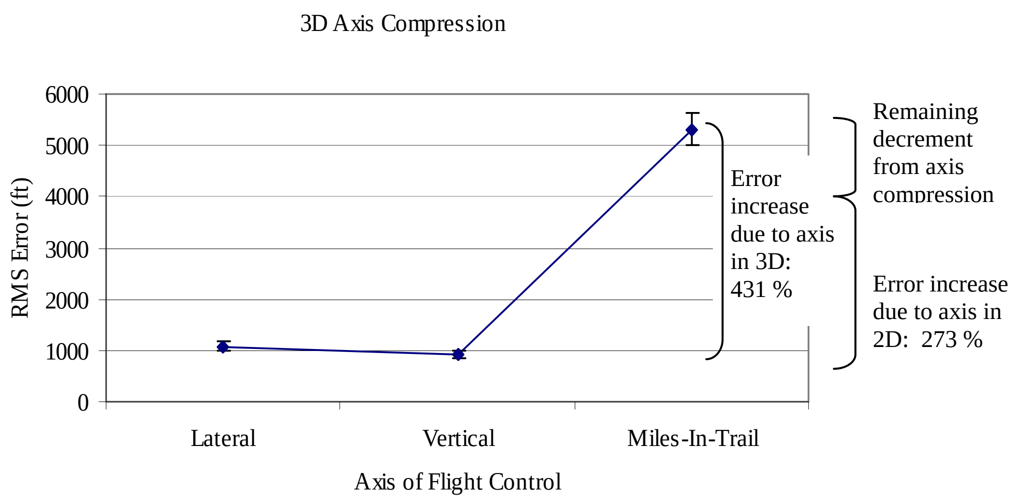
Estimation Probes. Distance and time probes were introduced as an assessment of estimation under less time-pressured and resource-limited conditions. Display size, manipulated through a reduction to 2D physical size or through 3D axis compression, had no significant effect on the absolute error of distance estimates ($p > 0.10$) or on the likelihood of pilots to over or underestimate distances between hazards ($p > 0.10$). Thus, explicit distance estimates were not subjected to display size contamination, given that ample time was available to use a more analytic approach to estimation. Whether pilots employed a computational or "laying off" strategy could be further assessed by examining the correlation of the length of the distance to be estimated to probe response time. To the extent that the laying off strategy was employed, response times to distance probes should be longer when the length to be estimated was longer, as pilots would need to mentally lay the scale along the distance more often. While this correlation was found to be significant on the pooled estimates of all participants ($r_{(982)} = 0.10$, $p = 0.001$), the magnitude of the correlation was strikingly small. Thus, while significance was found because of the high number of cases being analyzed, the limiting contribution of distance to variance in response time suggests that pilots were more likely to have used a computational approach when making estimates.

In the examination of time estimation, time was underestimated in all conditions by an average 37.2 s. While time estimates were also unaffected by 2D physical size ($p > 0.10$), when using the 3D display, pilots were found to underestimate time to a greater degree for estimates made along the compressed depth axis (48.8 s) relative the uncompressed lateral axis (37.0 s) ($t(14) = 3.9$, $p = 0.001$)., which reflects nearly a 33% effect. Thus, while relatively simple distance judgments could be made computationally, more complicated time estimates, reliant upon estimates of distance and traveling speed, were contaminated by axis compression.

Risk Assessment and Route Selection. Subjective estimates of route safety were examined as a measure of risk assessment used in route selection as well as to verify the effectiveness of the manipulations to path condition. When comparing estimates of the "safe," "unsafe," and "very unsafe" routes, subjective ratings of planned path safety were found to be significantly reduced as a function of the algorithmic ratings of efficient path safety ($F(2, 30) = 7.7$, $p = 0.002$). While the reduction in efficient path safety was manipulated to be linear (i.e., reducing at equal intervals) (see Table 5.1.1), the reduction in subjective safety ratings was not, reflecting a greater decrement in safety from the "unsafe" to "very unsafe" conditions ($t(15) = 2.6$, $p = 0.02$), than from the "safe" to "unsafe" conditions ($t(15) = 1.4$, $p = 0.18$), the latter of which was not significant. The overall trend, however, validates the general efficacy of the safety measure as well as the pilots' sensitivity to the differences in safety levels of the presented flight paths.



(a)



(b)

Figure 5.2.2. Magnitude of error increase as a function of the axis of flight control in (a) the 2D display and (b) the 3D display. Increase in error in the 3D display was significantly greater than that of the 2D display, suggesting that axis compression, regardless of the confounding effect of flight axis, increased RMS error. The decrement associated with 3D axis compression was greater than that for 2D physical size minification.

Table 5.2.1. Detailed descriptive analyses for the three axes of flight as a function of display size and dimensionality for Experiment 4. The *Comparisons* column describes the significant display size findings.

Dimensionality	Axis	Statistic	Small	Large	Comparisons
2D	Altitude	Mean	1421.2	1010.9	S > L
		SE	92.6	76.5	
	Heading	Mean	1660.4	1056.4	S > L
		SE	140.0	134.3	
	Miles-in-trail	Mean	5368.6	4255.8	S > L
		SE	305.1	339.0	
3D	Altitude	Mean	N/A	913.5	
		SE	N/A	81.3	
	Heading	Mean	N/A	1085.2	
		SE	N/A	105.5	
	Miles-in-trail	Mean	5313.1	N/A	
		SE	303.0	N/A	
					S > L

When subjective ratings were assessed as a function of display size, analyses indicated that pilots rated the efficient path as 20.5% safer when the decision scenario was presented on a large display (or uncompressed axis) relative to a small display (or compressed axis), regardless of whether size was manipulated through minification of 2D physical size or through 3D axis compression ($F(1, 15) = 14.6$, $p = 0.002$). Similar findings were reported for subjective ratings of the diversion path safety ($F(1, 15) = 3.6$, $p = 0.08$), though the effect was only marginally significant and was smaller in magnitude (about 6% increase). Thus, by simply representing the risky, or very risky) and display dimensionality did not modulate this effect ($p > 0.10$). The descriptive analyses for the safety ratings are depicted in Table 5.2.2.

Table 5.2.2. Descriptive measures for subjective plan risk and confidence as a function of dimensionality and size for Experiment 4. The *Comparisons* column describes the significant display size findings. Cells denoted as *NS* represent nonsignfiicant findings. The larger display representation led to higher estimates of safety for both path ratings and subjective confidence.

Measure	Dimensionality	Statistic	Small	Large	Comparisons
Short path safety	2D	Mean	3.9	4.5	L > S
		SE	0.2	0.2	
	3D	Mean	3.8	4.8	L > S
		SE	0.2	0.3	
Diversion path safety	2D	Mean	4.4	4.8	L > S
		SE	0.1	0.1	
	3D	Mean	4.5	4.7	L > S
		SE	0.2	0.2	
Selection Confidence	2D	Mean	5.3	5.6	L > S
		SE	0.2	0.2	
	3D	Mean	4.9	5.7	L > S
		SE	0.3	0.2	

To examine whether these size-inflated estimates of flight safety on the shorter path translated into a reversal in flight path preferences, a Chi-squared analysis was conducted to examine the number of trials in which pilots traveled the shorter route as a function of display dimensionality and display size. Though manipulations to the physical size of the 2D display influenced estimates of efficient path safety, these biased assessments did not translate into differences in path preference ($p > 0.10$). In contrast, axis compression in the 3D display *did* significantly influence path preference. Figure 5.2.3 plots the frequency with which the efficient path was selected as a function of axis compression in the 3D display and route safety. As shown in the figure, when the "safe" path condition was examined, axis compression did not influence flight path selection ($p > 0.10$). Thus, whether pilots were required to estimate distances from the flight path to impending hazards along the compressed or noncompressed axis had no influence on path preference when the shorter route was safe. When the shorter route was unsafe or very unsafe, however, the presentation of the hazard distance significantly influenced route preference. Specifically, when the short path was unsafe, pilots chose to travel the short route in only 3 of 16 trials (18.8%) when the distance between the hazard and the flight route was presented on the compressed axis. When this span was presented in a noncompressed form, however, this frequency significantly increased to 11 of 16 trials (68.8%), and this difference was highly significant ($X^2 = 8.1$, $p = 0.006$). A similar pattern was found when the planned route was very unsafe. Pilots estimating the distance from the flight path to the hazards along the compressed axis chose the shorter route in only 4 of 16 (25.0%) cases. When the span was presented along the noncompressed axis, pilots chose to travel the shorter but very unsafe route in 10 of 15 (66.7%) cases ($X^2 = 5.4$, $p = 0.02$). Collectively, the inflated estimates of risk and the resulting shifts in path preference provide overwhelming support for the accessibility model of route selection.

As a final measure of route selection performance, pilot's reported confidence in their flight route choice was assessed in response to shifts in display size. These analyses revealed that pilots were more confident when selecting routes presented with a large display format ($F(1, 15) = 15.2$, $p = 0.001$), slightly more so when size was manipulated through axis compression, as evidenced in the significant interaction of display dimensionality and size ($F(1, 15) = 3.0$, $p = 0.10$). This latter finding likely reflects the precision with which distance estimates could be made with a larger display and the lack of confidence associated with making estimates under low resolution conditions associated with display minification. Descriptive statistics for the confidence measure are also detailed in Table 5.2.2.

Figure 5.2.3. Percentage of trials in which pilots selected the efficient route as a function of path safety. Note that, when the span between ownship and hazards was depicted in the noncompressed scale, pilots were more likely to select the shorter route when it was unsafe or very unsafe, relative to trials in which the hazard span was presented in the smaller compressed scale.

5.3 Discussion: Experiment 4

Experiment 4 provides an overarching examination of the effects of display size, manipulated by changing two-dimensional physical display size or through axis compression in a three-dimensional display, on distance estimates used for flight control and risk assessment. Distance and time estimation probes were also examined in order to evaluate the feasibility of the computational approach to estimation when time and resources were less constrained.

Distance and Time Estimates. While Experiments 1 through 3 reported urgency and resolution contamination in implicit distance (deviation) estimates used under time pressure for flight control, little evidence was found in the current experiment for size contamination of explicit estimates made in response to distance probes. Thus, when single explicit distance estimates were made with ample time for an analytic assessment, pilots were able to overcome size contamination, choosing instead to implement a more computational approach. As probe estimation time was not found to be correlated with the length to be estimated, which would occur if the individual were to "lay off" the scale along the judged distance (Hartley, 1977), it becomes clear that estimates were computationally derived by assessing display distance in conjunction with display scale. These findings were consistent, regardless of the manner in which size was manipulated.

While pilots were adaptive in adjusting distance estimates as a function of display size when ample time was available, both physical size and axis compression led to contamination when estimates were difficult. Specifically, complex time estimates, which were reliant upon mentally integrated judgments of distance and speed, were biased in the predicted direction by axis compression, suggesting that higher cognitive demands drove pilots to use display distance as a partial indication of world distance because of the relative ease with which this information could be accessed (Kahneman, 2003). Thus, when explicit judgments of distance are required, the judgments are objective and unbiased by display size. When distance is assessed implicitly, as a vehicle for calculating time-to-contact, then display size contamination is manifest. As demonstrated many times, such contamination is also present in implicit distance judgments used to assess tracking error that needs to be corrected, and as a vehicle for calculating risk, both of which we now discuss.

Flight Path Control. Replicating the first three experiments, as well as findings reported in the literature (Abbott & Moen, 1981; Barfield et al., 1995; Boeckman & Wickens, 2001; Comstock et al., 2003; Ellis et al., 1991; Wickens et al., 1996), a reduction in display size produced an increase in flight control error, regardless of how display size was manipulated. As in the previous experiments, the degree of size contamination that was observed with display minification was significantly less (41%) than the degree of display size reduction (72%), suggesting that the performance decrement was driven at least in part by the lowered resolution of small displays. Furthermore, the size decrement associated with flight control error was equal across all three axes of flight. Thus, while findings from the first two experiments suggested that pilots prioritized one of the axes by allocating resources and thus urgency to this axis at the expense of the other two axes of flight, findings from the present experiment did not suggest differential performance effects as a function of flight axis. The decrement to flight control associated with axis compression in the three-dimensional display was much greater than that found with a reduction in the physical size of the two-dimensional display, replicating patterns from Experiment 2. Because the size effect was amplified with 3D axis compression, despite the fact that the degree of size minification was equal across physical size reduction and axis compression, the results point to the influence of urgency. This amplification of the display size effect for 3D axis compression, relative to 2D display size minification, will be discussed in greater detail in the General Discussion.

Flight Planning. The contamination of distance estimates as a function of size was also examined within the context of enroute flight planning, as pilots are required to estimate the span between ownship and environmental hazards in assessing flight risk. While the normative model posited that display size would not influence risk assessment or subsequent route planning, the presented analyses showed the contrary. Specifically, display minification, regardless of whether size was manipulated by reducing the physical size of a two-dimensional display or through axis compression in a three dimensional display, produced lower estimates of flight safety. Thus, pilots estimated the span between ownship's projected location and an impending hazard as smaller when the distance was presented in a smaller display scale. These findings provide additional support for the hypothesis that distance information is used without fully considering display scale as an estimate of world distance because of the ease with which the information can be accessed (Kahneman, 2003). While these biased estimates did not influence route selection when physical size was manipulated in the two-dimensional display, they did contaminate route choices with the three-dimensional display. In particular, pilots were found to select more conservative routes when the distance between ownship's projected location and an impending hazard was presented on the compressed axis. Conversely, when this distance was presented along the uncompressed axis, the distance was overestimated, leading pilots to choose the riskier flight route. Consequently, the results suggest that a simple change in the size of the representation of the flight route and environmental hazards produces a significant reversal in the pilots' preferences for optimizing safety or efficiency, and also point to the strong contamination of axis compression in distance estimation.

As in flight control, both resolution and accessibility could be identified as driving mechanisms in these findings. Some support for resolution is found in the increased subjective confidence of pilots in route selection with the larger display scale, which likely resulted because the larger display caused pilots to conclude that their choice was based on higher resolution information and was thus more accurate. To the extent that resolution was operating in the actual route selection process, the smaller sized display, which had lower resolution, may have induced pilots to resort to more cautious route planning because of the display's reduced information content. If this were the case, however, the biases demonstrated in route selection should have been equal across 2D display minification and 3D axis compression, as the resolution was equally lowered through both forms of size reduction. Contrary to this prediction, pilots in the present study were more likely to be biased when size was reduced through 3D axis compression. Because of this difference in route selection across methods of size reduction, accessibility remains the primary mechanism in explaining the observed performance effects.

Thus, in concluding the discussion of Experiment 4, we note that all three tasks depending on distance estimation were biased in the predicted direction when the estimate was implicitly required in the process of taking a subsequent action (time-to-contact, risk assessment and route selection, or flight control). Additionally, across both tasks (flight control and flight planning) where the 2D and 3D comparison could be made, the bias was greater with 3D axis compression than with 2D physical size minification.

CHAPTER 6: GENERAL DISCUSSION

Four experiments were conducted to measure the influence of display size on attention-based tasks, such as surveillance and search, as well as spatially-based tasks, including distance estimates used in flight control and risk assessment. Collective effects across the four presented experiments reveal four general trends that will be discussed in detail:

1. Display enlargement yielded only minimal costs, as shown in the reported surveillance and search effects for Experiments and surveillance analyses in Experiment 2.

2. Head movements were not needed to access peripheral display information, even in the largest display, suggesting the eye field may extend to 35 degrees in complex displays.

3. Effects of contamination were more pronounced with minification than with magnification, a finding which was reflected in the tendency to replace display distance for computed world distance, though only when distance estimates were implicit.

4. The observed implicit size contamination is more pronounced, and sometimes only observed, when display size was manipulated through 3D axis compression, relative to 2D physical size minification.

6.1 Display Enlargement and Surveillance

The primary goal of Experiments 1 and 2 was to assess the influence that physical display enlargement, accomplished by extending the display perimeter, had on attentional tasks of search and surveillance. It was hypothesized, based on the available literature (Enoch, 1959), that display enlargement would cause observers to neglect peripheral display regions and that this effect would operate based on the additional resources and effort needed to extend attentional scan patterns to largely displaced stimuli (Muthard & Wickens, 2004; Wickens, 1992), as well as the lowered resolution of the attentional field in those regions (Carrasco et al., 1995; Carrasco & Frieder, 1997). While these mechanisms were operating to an extent, as evidenced in the degraded detection of events as they neared the display's periphery and the neglect of these regions in attention allocation (Baker et al., 1960; Schoonard, Gould, & Miller, 1973), the "edge effect" was not amplified when the display was enlarged, even though a greater proportion of the display lay within the periphery. Rather, pilots strategically *compensated* for the changes in size by maintaining attention allocation to the most peripheral display region and shifting attention to new areas that required foveation to access. In fact, strategic compensation was the selected approach for pilots even when a subsequent tracking task was sapping attentional resources and when several information sources had to be integrated during search.

The only influence that display size had on surveillance was for display minification to amplify the negative effects that display clutter had on event detection. Thus, while clutter resulted in lateral inhibition and masking (Carrasco et al., 1995; Carrasco & Frieder, 1996; Carrasco & Yeshurun, 1998) through the limits of attentional resolution (Intriligator & Cavanagh, 2001; Tripathy & Cavanagh, 2002), these effects were worsened when the display was minified and the stimulus density was correspondingly heightened. It should also be noted that while the present study examined surveillance with a raster map, in which changes to the size of the display produces proportional changes to the size of all of the symbols and text within the display, these decrements could be amplified in a vector map. In such a display, the size of map features are often kept constant in size with display minification, resulting in a reduction in the spacing between display elements and amplified display density above and beyond that associated with simple vector display minification (Van Olffen, Wickens, & Muthard, 2003). Collectively, the results suggest that display enlargement produces superior surveillance performance, especially for highly cluttered displays, even though additional resources must be used to monitor the expanded display area. One possible reason why no costs of effort compensation were found is because, despite our intentions to do so, even the largest display did not extend to a region where the more effortful head movements were required to survey the periphery.

6.2 Defining the Eye and Head Fields

While surveillance was discussed primarily in terms of eye movements, the extent to which pilots utilized head movements to access information was also measured. Interestingly, pilots rarely used head movements to monitor the displays, even with the largest display size, which subtended over 35 degrees of visual angle. While research has indicated that the eye field can extend to display angles as wide as eighty degrees of visual angle (Sanders, 1970), other more conservative estimates, based on data collected in more naturalistic circumstances, place the origin of the head field at 40 degrees (Robinson, Koth, & Ringenbach, 1976). In fact, estimates from complex visual scenes suggest that eye response times significantly slow for magnitudes of 24 degrees of visual angle (Swanston & Walley, 1984) and that saccades rarely extend more than 15 degrees (Bahill et al., 1975).

In the present experiments, however, pilots were able to access peripheral information that was separated by more than 35 degrees (17.5 degrees to the left and right of the screen center) without implementing head movements and without performance suffering disproportionately when the large display was used. It is also important to note that the contrast of the targets on the integrated hazard display was not high, making information more difficult to view with the periphery (Robinson et al., 1976), which should have increased the likelihood of pilots to use head movements to access information had eye movements alone not been sufficient. Given these results, perhaps the size of the eye field should be extended from the conservative estimates made in naturalistic settings (Bahill et al., 1975), or at least be presented as a widely varied range. Additional research with complex dynamic displays, examining surveillance across a wider range of display sizes than those used here, should be conducted to begin to formally define the limit of the eye field and origin of the head field or the factors that influence the boundary between the two.

6.3 Display Minification and Implicit Distance Estimates

Tracking. While the attentional tasks of search and surveillance were largely uninfluenced by changes in display size, this was not true for implicit distance (i.e., deviation) estimates used in tracking. In fact, in all of the presented studies, size minification was found to consistently increase error for at least a portion of the axes being tracked. This evidence, presented in conjunction with literature that has showed similar findings (Abbott & Moen, 1981; Boeckman & Wickens, 2001; Comstock et al., 2003; Hendrix & Barfield, 1994; McGreevy & Ellis, 1986; Yeh & Silverstein, 1992), can be used to reject the sole contribution of the normative model in describing the obtained findings. Specifically, we can conclude that display size, whether it is manipulated by changing the physical size of a two-dimensional display or through axis compression in a three-dimensional display, *contaminates* the estimates of path deviation used in tracking.

The resolution and urgency models were both proposed as causal models for this contamination and were found to account for the display size differences found in tracking in all of the presented experiments. Two lines of support for the resolution model can be noted from the presented data. First, tracking error was found to increase *nonlinearly* with decreases in physical display size, replicating findings from previous research (Comstock et al., 2003). Specifically, in Experiments 1 and 2, performance decrements were only associated with display minification when the display was reduced to the smallest of the three display sizes (see Figures 2.2.1 and 3.2.1). Thus, we can conclude that poor resolution led to the observer's failure to perceive small sub-threshold deviations and thus the failure to correct them. When the display was enlarged so that the smaller errors were above this threshold, however, pilots were able to perceive and correct errors that were not visible with the most minified display.

The second source of support for contributions of the resolution model can be found in the lack of modulation of the size effect when resources were more limited (e.g., from single to dual axis control in Experiment 3). While some decrement was associated with the control of more than one axis in Experiment 3, display size did not amplify this effect, suggesting that the display size effect was data limited, rather than resource limited (Norman and Bobrow, 1975). Thus, it is possible that the reported display size findings were not influenced by resource allocation, but by perceptual limitations, which are the driving force of the resolution model. It should be noted however, that while resource shortages did not amplify the reported display size decrement, the dual task manipulation may not have provided a sensitive form of imposing task load. Thus, while increasing axis control load did result in scanning costs, it may not have taxed mental resources, suggesting that the differences in control load were not substantial enough to have produced any differences in performance or to interact with display size. A less empirical evaluation of the amplifying effects of task load on display size, however, can be made by comparing size contamination of tracking for Experiment 1, where pilots performed three tasks simultaneously, with that of Experiment 2, where pilots performed only two tasks. In this comparison, size contamination was not amplified with additional resource competition of Experiment 1, thus supporting results from Experiment 3 and the potential role of resolution as the operating mechanism in size contamination.

Although resolution limitations constrain tracking performance, urgency was also found to operate as a form of size contamination. Evidence for the urgency model can be found in the modulation of the display size effect by how size is manipulated. To the extent that the size decrement could be attributed solely to perceptual limitations and was equated in magnitude across the two means of size manipulation, these limitations should be equivalent. That was not the case here, across both Experiments 3 and 4. Repeatedly, the analyses suggested that 3D axis compression induced greater costs to performance than reductions in 2D physical size of the same magnitude. This finding validates the collective conclusions that can be taken from the literature, which clearly note a stronger size influence on tracking when display size is manipulated through axis compression (Boeckman & Wickens, 2001; Hendrix & Barfield, 1994; McGreevy & Ellis, 1986; Wickens et al., 1996; Yeh & Silverstein, 1992) when compared to the sparse findings for physical display minification (Abbott & Moen, 1981; Comstock et al., 2003). While the possible underlying cause for this urgency modulation effect will be considered in the following section, its importance here in validating the urgency model should not go unnoted.

Collectively, these data have clearly implicated the dual roles of resolution and urgency as causal factors in explaining the reported size effects. It should be noted, however, than in most of the reported cases, the performance decrement associated with display minification was *not* equal in magnitude to the degree of display minification. Table 6.3.1 provides a detailed report of these ratios for each of the four experiments. To the extent that urgency was purely operating, without the influence of the normative models, the ratios of display minification and performance decrement would have been equivalent. Thus, while the data suggest the contamination of display size, through mechanisms of resolution and display distance accessibility (urgency), display scale was not fully ignored in tracking.

In fact, in two of the three experiments in which it could be measured (Experiments 1 and 4), the miles-in-trail axis was the *least* susceptible to size contamination of the three axes of flight, and contamination for this axis in Experiment 3 was less than half of that expected as a function of display reduction. While tracking for the lateral and vertical axes was depicted only spatially, the task of maintaining the miles-in-trail axis was always framed within the context of *world units* (e.g., maintain 5 mile separation). In presenting the task in this manner, pilots may have more explicitly considered the display scale in maintaining control of this flight axis relative to the others, a finding which has direct implications for display design and task framing. Alternatively, pilots attempting to maintain an accurate lateral and vertical position, while presented with display scale information, were not specifically instructed to consider this information during tracking. This fact may have made estimation along these axes less conscious and less explicit and thereby may have driven contamination to higher levels for the vertical and lateral axes in Experiments 1, 2, and 4. Support for this conclusion can also be found in the relatively low rates of contamination for tracking in Experiment 3, where pilots were also explicitly instructed to maintain aircraft position as a function of *world units*, rather than displayed deviation. Thus again, a greater degree of explicit guidance appears to reduce (but here, not eliminate) the magnitude of size contamination.

Time-to-Contact and Risk Assessment. As with tracking, judgments of time-to-contact and estimates of risk are dependent on *implicit* distance judgments, which must be made efficiently and usually feed into a larger, more global task. Consistent with the results reported for tracking, display size was found to contaminate these judgments, yielding estimates that were biased by display scale. As a result, time-to-contact was underestimated to a greater degree when the judgment was made along a minified axis, though only when size was manipulated through axis compression. Safety estimates, which were reliant upon implicit estimates of the distance from a pilot's own aircraft to environmental hazards, were inflated by about 12% with display enlargement, regardless of how display size was manipulated. Finally, when size was manipulated through axis compression, pilots chose routes that traveled more closely to hazardous terrain, traffic aircraft, and poor weather when these distances were represented with a larger display scale, which represents an even more implicit assessment of the influence of distance estimates. Collectively, these findings point to the influence of display distance *accessibility* in implicit distance estimation. Thus, pilots utilized display distance as proxy for world distance without fully considering the scale of the display.

Table 6.3.1. Table details the degree of display reduction when the display was reduced from large to medium and from medium to small. Correspondingly, the degree of performance reduction for each display reduction is also shown. Nonsignificant findings are indicated by "NS." Note that a negative reduction in error is equivalent to an improvement in performance. Performance reduction only matched display reduction for the altitude measure when the display was minified from medium to small.

Experiment	Axis	Medium to Small	Large to Medium
Experiment 1	Display Reduction	50.0 %	44.4 %
	Altitude	81.9 %	NS (37.6 %)
	Heading	41.7 %	NS (15.0 %)
	Miles-in-trail	NS (2.4 %)	NS (1.3 %)
Experiment 2	Display Reduction	50.0 %	44.4 %
	Altitude	56.3 %	NS (4.3 %)
	Heading	NS (7.1 %)	NS (10.2 %)
	Miles-in-trail	23.3 %	NS (-13.1%)
Experiment 3	*Reduction*	*Large to Small*	
	Display Reduction	50.0 %	
	Performance Reduction	14.0 %	
	Activity Reduction	27.0 %	
	Axis	*Large to Small*	
Experiment 4	Display Reduction	72.2 %	
	Altitude	40.6 %	
	Heading	57.2 %	
	Miles-in-trail	26.1 %	

While all of these findings point to the influence of display distance accessibility, resolution may have also influenced estimates to some degree. Specifically, pilots reported having greater confidence when assessing flight risk and selecting flight routes with a larger display scale, which was likely driven by the higher resolution and finer grain associated with the enlarged display. Thus, more detailed information about hazard and path location, easier hazard speed perception, and ease in reading textual data tag, all of which could be associated with the larger display, may have raised pilot confidence in path selection, even though performance was worsened.

6.4 Amplified Size Effects with 3D Axis Compression

An emerging trend from the presented data is the finding that size effects on implicit distance estimation were amplified when size was manipulated through 3D axis compression relative to 2D physical size minification. This trend was apparent in tracking performance and control activity, time-to-contact estimates, route selection, and planning confidence in Experiments 3 and 4. Some evidence for this trend was also revealed by noting the large body of evidence that exists to suggest that distance estimates, either explicit or implicitly used in tracking, are contaminated by 3D axis compression (Boeckman & Wickens, 2001; Hendrix & Barfield, 1994; Jasek et al., 1995; McGreevy & Ellis, 1986; Merwin & Wickens, 1996; O'Brien & Wickens, 1997; Wickens & Prevett, 1995; Wickens et al., 1996; Yeh & Silverstein, 1992), relative to the sparse and less consistent literature for physical size minification (Abbott & Moen, 1981; Chapanis & Mankin, 1967; Comstock et al., 2003), though this difference alone was not evidence enough to firmly predict the strong findings from Experiments 3 and 4. In fact, we found no research that directly compared these two methods of manipulating display size.

Two reasons can be proposed to explain why 3D axis compression induces stronger size contamination than physical size minification in a 2D display. First, the presentation of the depth information in the 3D display likely leads to geometric foreshortening, which can be manifest as *slant underestimation* (McGreevy & Ellis, 1986; Perrone, 1982). Slant underestimation refers to the tendency to rotate a surface viewed in depth toward the viewing plane and away from the line of sight, thus estimating the surface to be steeper than it truly is. Consequently, this vector can be perceived as longer vertically, but when measured in depth, the vector is perceived as shorter. A second mechanism that may be amplifying the size effects in axis compression is the use of two different display scales in an integrated presentation. In contrast to the means of compression used by minification in the 2D display, in which two display scales were presented alone or in separate panels, the 3D display was always used to present two different display scales simultaneously in an integrated fashion. Presenting the two different, incompatible display scales in an integrated form may have created confusion (Fracker & Wickens, 1989) and increased complexity, thus requiring mental resource allocation to maintain the different scales in memory and apply those scales to distance estimates. As a result, pilots likely resorted to more implicit estimates of distance, which were not fully reliant on the scale of the display. We note that both of the above explanations are speculative and warrant further investigation.

6.5 Conclusions

The presented results have both theoretical and practical implications for the understanding of the effects of display size on both attentional and spatial tasks. Theoretically speaking, the findings suggest that Kahneman's (2003) notion of *accessibility,* proposed to describe the availability of attributes in the process of diagnosis and judgment, was found to extend to spatial tasks. Specifically, the presentation of distance in display units, which serves as an accessible percept for a distance or time-to-contact estimate, is perceived automatically and effortlessly (Tversky & Kahneman, 1983). It is only with the deliberate implementation of attentional resources, needed to consider display scale information in conjunction with display distance information, that world distance can be explicitly assessed. With this latter approach, estimates of distance will not be contaminated by display size. Because this deliberate process is dependent on available time and resources, it becomes lax (Kahneman & Frederick, 2002) when several tasks are performed in conjunction with the distance estimation task, such as search and surveillance, when several distance estimates must be made simultaneously, as in risk assessment, or when estimates must be made continuously over a long period of time, as in flight control. Under such circumstances, the *display distance* attribute was found to be more heavily weighted, at the expense of display scale, in the estimation of world distance.

From a very different theoretical perspective, the results from the surveillance findings also provide theoretical support for the zoom lens model of attention (Ericksen & St. James, 1986) in complex visual scenes. Specifically, display enlargement was found to result in an enlargement in the breadth of attention, implying that attentional patterns are adaptive in response to changes in the size or scope of the visual scene.

Several practical guidelines for display design can be established in response to the presented results. The results encourage a view that display size, whether manipulated by reducing the physical size of a 2D display or through axis compression in a 3D display, affects attentional and spatial tasks. Figures 6.5.1 and 6.5.2 depicts these relationships for 2D physical size and 3D axis compression, respectively. In placing all of these tasks in a single figure, we are reinforcing the notion that an integrated hazard display will often be asked to serve several tasks concurrently in the advanced cockpit. First, note that for the tasks of surveillance and search, displays can be enlarged to encompass at least 36 degrees of visual angle without producing performance decrements. Given the effort associated with monitoring information located within the head field, however, extreme caution should be taken in enlarging a display much beyond this size, as performance would be expected to drop exponentially. Thus, this guideline is constrained by the range of display sizes evaluated here. Also shown by the grey line extending from the surveillance and search performance model from the medium to small display in Figure 6.5.1 is the degrading effect that display *minification* has in a highly cluttered display. Thus, to the extent that the display is highly cluttered and minified, where display elements are located within 0.05 degrees of one another in the fovea or 3 degrees of one another in the periphery, performance would diminish (Intriligator & Cavanagh, 2001). While not directly examined, display minification would also be expected to produce decrements in reading both text and geometric symbols, both of which might be necessary for search or surveillance, and such degradation would obviously be amplified under poor viewing conditions such as low illumination or low contrast.

For displays designed to support spatial tasks, the recommendations are very different. To the extent that explicit estimates are made, for which display scale and display distance are both used in making judgments, display size will have no effect on resulting performance and optimal display size can be determined by available display real estate or by assessing the optimal size for other tasks supported by the display. For the task of flight control, the data suggest that overall display size should be no less than 20 degrees by 15 degrees of visual angle, with an attitude directional indicator that is no smaller than 2.3 by 1.1 degrees, as an ADI smaller than this key size produced decrements in flight path maintenance across all four experiments. For most aircraft, these guidelines are well adhered to, however, some concern may be expressed regarding back-up instruments (J. Fox, personal communication, April 12, 2005) or remote control stations for unmanned aerial vehicles. For estimates used for risk assessment and route selection, displays sized at 10 degrees by 7 degrees will produce higher estimates of risk and, at least for 3D displays, more conservative route choices than their larger counterparts (36 degrees by 27 degrees). Because this latter set of tasks was only evaluated with two display sizes, determining a point at which performance levels as a function of size is not possible. These discussed performance effects for distance estimation, as shown in Figure 6.5.1, are amplified when size is manipulated to an equal degree through axis compression, as depicted in Figure 6.5.2. Thus, more conservative estimates of size should be taken when applying these guidelines to the design of 3D displays and determining an optimal elevation angle. It should also be noted that, with extreme minification to degrees much smaller than what was investigated here, many of the performance variables would exhibit highly degraded performance, as resolution would take over as the sole driving mechanism. On would hope that pilots, losing resolution, would therefore bias on the side of caution in assessing separation distances from hazards and selecting flight routes, but there is not guarantee that this will happen.

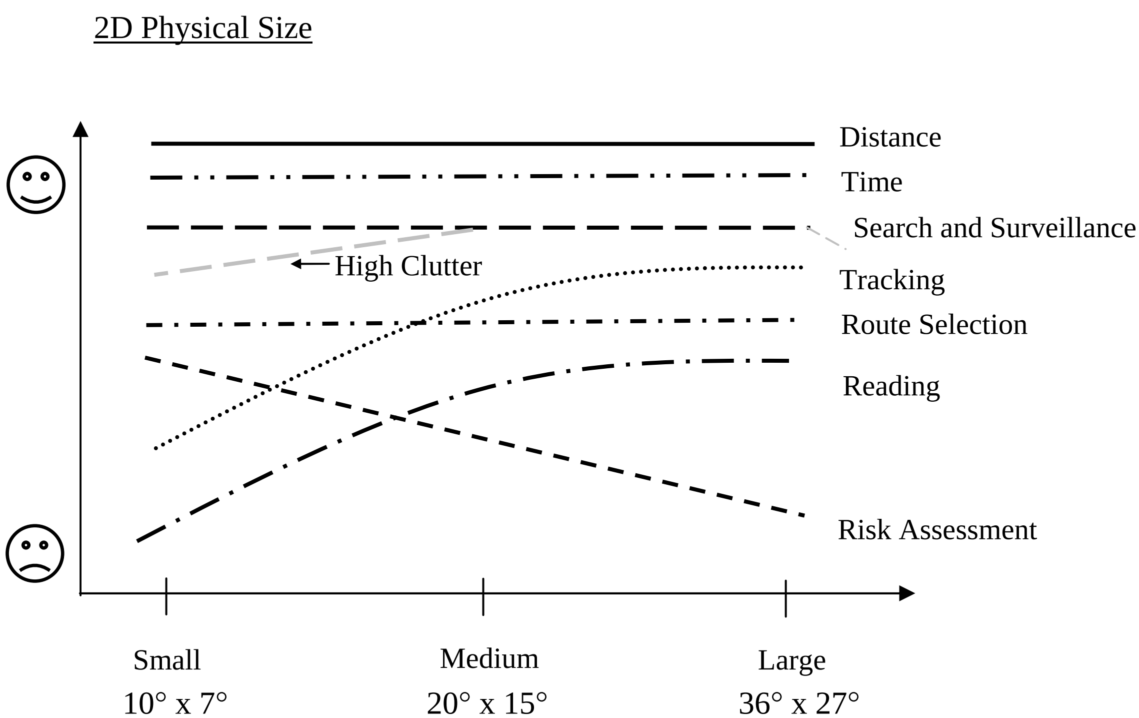


Figure 6.5.1. A global model of the effects of physical display size on distance and time estimation, search and surveillance, tracking, route selection, and risk assessment, as supported by the data from the presented experiments.

3D Axis Compression

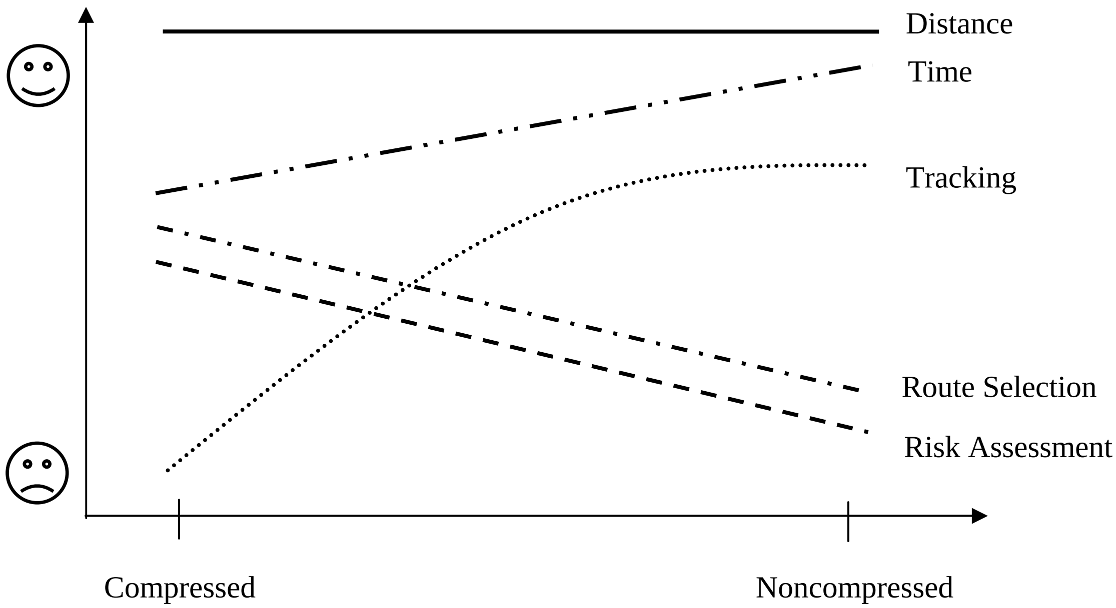


Figure 6.5.2. A global model of the effects of axis compression on distance and time estimation, tracking, route selection, and risk assessment, as supported by the data from the presented experiments.

Additionally, while the four experiments present conclusive evidence for the presence of size contamination of implicit distance estimation, the unique contributions of resolution and urgency were not fully disentangled. A complete and quantitative examination of the influences of resolution and urgency can be carried out by empirically evaluating flight control activity and tracking error as a function of deviation size through a spectral analysis. This assessment would reveal the control activity for the smallest deviations, and, to the extent that no stick movement is made in response to these deviations in the small display alone, the contribution of the resolution model could be fully confirmed. While this evaluation was not possible in the present experiment, because of the complexity of the flight simulation and the large variance in the control data, this analysis would provide a fruitful area of examination in future studies. Lastly, two additional means of manipulating display size, namely changing an observer's viewing distance from a display surface and varying a display's field of view or map scale, were also not evaluated in the present experiment. Given the difference in the size effects associated with 2D physical size minification and 3D axis compression found in the present experiments, these methods of manipulating display size might be expected to influence performance in a variety of unique ways. With regard to the first of these, one could, for example, imagine vastly different visual angles with which a hand held display might be viewed, varying distance by factors as large as 3:1. With regard to the second, it is noteworthy that most electronic pilot maps and GPS navigational units have adjustable gains which could therefore greatly influence route selection as a function of what gain was chosen.

To address some of these limitations, future work to examine the influence of display size on attentional and spatial tasks could evolve in at least four directions. First, the range of physical display sizes could be extended to determine the origin of the head field for complex dynamic displays so that more specific guidelines could be given as to the upper limit for display enlargement. Second, the range of display scales that were evaluated could be expanded to include display magnification, as might be used in displays for laparoscopic surgery, and panoramic wall mounted displays, as used to monitor air traffic across the country at the FAA command center. Third, to fully confirm the contribution of the resolution model in display size effects on tracking, a spectral analysis could be performed on carefully controlled activity data. This method would examine the presence of control activity as a function of deviation size and reveal whether participants were not tracking, and thus not perceiving, the smallest errors when portrayed in the smallest display. Finally, the effects of viewing distance and display field of view should be empirically assessed to determine the differential effects that these manipulations might have on both attentional and spatial tasks. As only one method of size was evaluated for the attentional tasks, this approach could reveal differential size effects for search and surveillance that were not examined in the present experiments.

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APPENDIX A

EXPERIMENT 1 - INSTRUCTIONS

With the influx of new technological advances, aircraft have been outfitted with displays and electronic maps. Often, the sizes of these displays must be reduced in order to accommodate all of the new technology within the limited space of the cockpit. To understand how display reduction may affect performance, NASA Ames has asked us to evaluate the effects of varying the size of electronic maps on a variety of tasks that pilots may need to carry out.

TASK 1: AVIATING

At the beginning of every trial, ownship will be heading north at an altitude of 15,000 ft and at a speed of 150 knots. Your first task is to keep heading and altitude constant at these target values. You can use the joystick attached to your seat to control these flight dynamics. Your altitude is represented as a digital altimeter in the data tag next to ownship. The pitch of the aircraft is represented in an ADI which is located directly below ownship. You should use the joystick to make changes in the altitude of the aircraft as necessary and then return the aircraft to level pitch to maintain the target altitude. Heading is represented by the aircraft icon representing ownship. When the nose of the aircraft is not pointing due north, a correction in heading should be made.

A lead plane is located 5000 meters in front of ownship. This lead plane will occasionally slow down and accelerate. Your task is to maintain a distance of 5000 meters between ownship and the lead aircraft by using the joystick. The left button on the joystick will cause your aircraft to slow down, while the right button will cause your aircraft to accelerate. A scale, showing the represented distance of 5000 meters, is shown on the right side of the display.

TASK 2: ANSWERING QUESTIONS

In the upper right hand corner of the display, you will occasionally be presented with multiple-choice questions about the features on the map. The corresponding answer (i.e., A, B, C, or D) can by typed in using the keyboard and the four adjacent keys marked with each of these letters. You should try to locate the relevant information on the map and answer the question as rapidly as you can. In these questions, the term “feet” refers to flight level. Thus 140 ft refers to a flight level of 140 or 14,000 feet.

TASK 3: CHANGE DETECTION

During each trial, the other air traffic and weather systems may change their heading, speed, or altitude. Each plane is alphabetically lettered and has information about its altitude, heading, and speed. For weather systems, only altitude information is presented, but the heading and speed of these weather systems can be obtained by watching their movement. You should monitor the airspace to detect these changes. As soon as you notice any change in these potential aviation hazards, you must press the space bar and verbally inform the experimenter of the change that you noticed. Planes can be identified by their letter code, and weather patterns can be identified by their altitude. Changes, especially in the weather patterns, can be very difficult to notice. Therefore, you must stay alert and vigilant of the current state of all aircraft and weather systems during the entire trial. You do not need to verbally report changes in your own aircraft or the lead plane, but remember you do need to control your plane to match the lead plane speed.

There is one practice trial and six experimental trials in the experiment. Between each of these trials, you will have an opportunity to take a break if you would like. If you have any questions, please ask the experimenter at any time during the course of the experiment.

APPENDIX B

EXPERIMENT 2 - INSTRUCTIONS

As electronic maps become a fixture in the cockpit, designers are interested in determining the optimal size and format of these displays. NASA Ames Research Center has asked us to evaluate these issues on a variety of tasks that pilots may need to carry out in the cockpit.

You will complete two types of tasks, namely (1) aviating and (2) hazard monitoring.

Aviating

Your own aircraft will be represented on the display with a light blue aircraft icon. It will always be located at the center of the display, and other traffic and weather will move relative to your aircraft. At the beginning of the trial, your aircraft will start off with an altitude of 15,000 ft, a speed of 170 knots, and a north-up heading. Located directly below your aircraft is an attitude directional indicator, or ADI, which will show your bank and pitch. Your task will be to maintain the north-up heading of your aircraft, as well as to maintain your target altitude of 15,000 ft, by correcting any deviation in heading and altitude as soon as possible. The joystick located to the right of the monitor can be used to make these flight maneuvers.

Directly north of your own aircraft is a lead aircraft, which will fly the same route as you. This lead aircraft will speed up and slow down occasionally throughout the trial. Your task will be to maintain a 7 mile separation from the lead aircraft by increasing or decreasing your airspeed. The trigger button located on the front of the joystick will increase speed, while the round button on the top of the joystick will decrease airspeed. A map scale is located on the right side of the display to assist in determining the separation distance.

Hazard Monitoring

During the each trial, the air traffic and weather patterns shown on the display may change their heading or altitude. Each aircraft is labeled with a digital data tag that displays information about its altitude. The weather patterns also have a digital tag that conveys altitude information, but it is located in the center of the weather pattern. Heading information, for both the traffic aircraft and the weather patterns can be deduced by watching their movements across the display.

Your task is to monitor these hazards in the airspace to find changes to aircraft or weather pattern altitude or heading. As soon as you notice any change in these hazards, you must press the space bar and verbally inform the experimenter of the change you noticed. Changes, especially in weather patterns, can be very difficult to notice, so please stay alert and vigilant of the current state of all of the aircraft and weather patterns during the entire trial. You do not need to report changes in your own aircraft's or the lead aircraft's heading or altitude.

In some trials, there will also be grey traffic aircraft that have data tags that read “No Data.” These aircraft simply represent additional aircraft in the air that are flying altitudes much higher or lower than your own, and thus require no monitoring. These aircraft will *never* change in heading or altitude, so you do *not* need to monitor them.

Summary

In summary, you will complete two tasks. Your first task is an aviating task, in which you must maintain the north-up heading and altitude (15,000 ft) of your aircraft. You must also stay 7 m from the lead aircraft, which can be accomplished by varying your airspeed. Your second task is to examine the airspace to find changes to the heading or altitude of weather systems or traffic aircraft. If you detect a change, press the spacebar and verbally inform the experimenter which hazard changed. Grey aircraft, which have data tags that read “No Data,” will never change, and thus do not need to be monitored.

You will complete 1 practice trial and 12 experimental trials, each of which lasts 7 minutes. The entire experiment will take about 2 hours. Between each trial, you will have an opportunity to take a break, if needed. If at any time you wish to end the experiment, you are free to do so. You may also ask questions at any time throughout the experiment.

Thanks again for volunteering to participate. The experimenter will address any questions you may have.

APPENDIX C

EXPERIMENT 3 - INSTRUCTIONS

With the influx of new technological advances, aircraft are being outfitted with electronic displays that depict ownship in relation to both air traffic and weather systems. This information can be depicted in either a top-down two-dimensional form, showing movement in only two axes of space, or in a three-dimensional display, which depicts all three axes of movement. Display designers are still unclear as to which format results in superior flight control, so NASA has asked us to evaluate simple manual control with both display formats.

TASK

In this experiment, you will be asked to complete several tracking tasks with different display configurations. Your main goal will be to keep the round ball icon, which could represent your aircraft, within 500 m of the goal position, which is represented with a large "+". The scale of each display is shown in the lower left hand corner, and tick marks located 250 m apart along the edge of the display will further aid you. In the experiment, you will complete the tracking task using either a 2D or 3D display.

2D Display

For the 2D display, you will be asked to track either the vertical or horizontal axes separately or simultaneously. When tracking the vertical axis, you will use the left joystick. When tracking the horizontal axis, you will use the right joystick. When you are asked to track both axes simultaneously, both joysticks should be used.

As is the case when you are controlling your aircraft, moving the joystick forward will pitch your aircraft icon downward. Moving the joystick backward will pitch your aircraft upward.

3D Display

When using the 3D display, you will either track either the horizontal or the depth axes separately or simultaneously. Only the right joystick will be used when tracking with the 3D display. Unlike tracking with the 2D display, moving your joystick forward will move the icon forward in depth. Moving the backward will move the icon backward in depth.

Prior to the beginning of each trial, you will be informed of both (a) the display you will be using (2D or 3D), and (b) which axes you will be asked to control.

There will be 2 practice trials and 9 experimental trials in the experiment. Between each of these trials, you will have an opportunity to take a break if you would like. Each trial will last 2 minutes, and the total experiment should take less than a half an hour. If you have any questions, please ask the experimenter at any time during the course of the experiment.

APPENDIX D

EXPERIMENT 4 - INSTRUCTIONS

As electronic maps become a fixture in the cockpit, designers are interested in determining the optimal format of these displays. NASA Ames Research Center has asked us to evaluate these issues on a variety of tasks that pilots may need to carry out in the cockpit.

The Display

During the experiment, you will be using a display that consists of two panels. The largest panel of the display is the integrated hazard display, which will present traffic, weather systems, and terrain in the airspace. The traffic aircraft will be labeled with their altitude (e.g., 150, which represents 15,000 ft) and a call sign (e.g., AA612). The terrain will be labeled with a three digit number representing the altitude of their peak (e.g., 132, which represents 13,200 ft). Weather systems will also be labeled with a three digit number representing the altitude of the weather top (e.g., 89, which represents 8900 ft). On the display will be two flight paths. Along each flight path are waypoints, designated by small bow tie symbols. The altitude of each flight leg is shown at each waypoint.

The smaller display panel, located directly above the integrated hazard display is called your primary flight display. This display shows a zoomed in version of your flight path, your aircraft (blue), and a lead aircraft (white) from a side view and a top-down viewpoint.

During the experiment, the displays will be presented in several different formats. For some trials, the integrated hazard display and primary flight display will be presented as two-dimensional (2D) displays. The 2D display will either be presented as a large display, which will take up most of the screen, or a small display. During the remaining trials, the displays will be presented as three-dimensional (3D) displays. The size of the 3D displays will not change.

Using these displays, you will complete three types of tasks, namely (1) flight path selection (2) flight control, and (3) answering questions.

Flight Path Selection

In each trial, you will be presented with two fight paths. The planned path is the straight line path and is the more efficient route. The path that deviates from the planned path is called the alternate path and is the less efficient route. Your first task will be to select one of the two flight paths. In making your choice, you should try to select the flight plan that will optimize efficiency, as long as it does not sacrifice flight safety. We will define safety as how close your aircraft comes while traveling along the flight path (vertically and laterally) to terrain, weather, or traffic aircraft. You will have 30 seconds to make your choice. After you make your flight path choice, use the mouse to input your choice. You’ll then need to enter your confidence in your selection. Confidence will range from 1 to 7, using the scale below:

1	2	3	4	5	6	7
Very Uncertain	Uncertain	Somewhat Uncertain	Neutral	Somewhat Certain	Certain	Very Certain

After rating your confidence, you'll need to rate the relative safety of each path. You can use the scale below for your ratings.

1	2	3	4	5	6	7
Very Unsafe	Unsafe	Somewhat Unsafe	Neutral	Somewhat Safe	Safe	Very Safe

Flight Control

After choosing your flight path, your task will be to fly along the selected route. Since the primary flight display represents a more detailed view of your aircraft and flight path you should use this display for flight control. The upper panel of the primary flight display will show your lateral orientation relative to the flight path, while the lower panel of the display will show your vertical orientation. You can control your lateral and vertical position by inputting the appropriate controls with the joystick. Located next to the primary flight display is an attitude directional indicator (ADI) which will show your bank and pitch and should assist you in flying the aircraft. Directly in front of your own aircraft is a lead aircraft, which will fly the route that you have selected. This aircraft will speed up and slow down occasionally throughout the trial. Your task will be to maintain a 5 mile separation from the lead aircraft by increasing or decreasing your airspeed. The trigger button located on the front of the joystick will increase speed, while the round button on the top of the joystick will decrease airspeed. A map scale is located next to the display to assist in determining the separation distance.

Questions

Every 30 seconds, a question will appear in the upper right corner of the screen, asking you to make a distance or time judgment. Example questions include "How far is AA612 from the mountain at 13,200 ft?" or "How long will it be until AA612 reaches the center of the weather cell at 8900 ft?" You will input your responses in the question box by using the keyboard. In answering distance questions, you should estimate the distance from the center of the first hazard to the center of the second hazard. All of your distance responses should be in miles, and you can use decimal points if necessary (e.g., 3.6 miles). In answering time questions, you should estimate the amount of time it would take for the aircraft to reach the perimeter of the hazard. Your time responses should be in seconds (e.g., 90 seconds). If you predict it will take two minutes until the plane reaches its destination point, your response would be 120 (2 minutes = 120 seconds). There will be 10 questions in each trial.

You will complete a total of 1 practice trial and 18 experimental trials. Each trial is about 6 minutes long. You are free to ask questions or take a break at any time. As your participation is voluntary, you are also free to stop the experiment at any time. Thanks again for your participation.

APPENDIX E

RISK ALGORITHMS

Plane Risk (P)

$\Delta A_{plane} = |\text{ownship altitude - plane altitude}|$

$\Delta L_{plane} = |\text{ownship latitude - plane latitude}|$

$$P = \left[\frac{5.0}{1.0 + \left(\frac{\Delta A_{plane}}{1000\ \text{feet}}\right)}\right] X \left[\frac{5.0}{1.0 + \left(\frac{\Delta L_{plane}}{3.0\ \text{miles}}\right)}\right]$$

Terrain Risk (T)

$\Delta A_{terrain} = \text{ownship altitude - terrain summit}$

If $\Delta A_{terrain}$ > 3000, T = 0

If $\Delta A_{terrain}$ < 0, T_A = 5 (the maximum value for T_A)

If $\Delta A_{terrain}$ > 2000, $\Delta L_{terrain}$ is measured from the summit position

If $\Delta A_{terrain}$ < 2000, $\Delta L_{terrain}$ is measured from the terrain outer edge at ownship altitude

If ownship is within the outer edge of the terrain at that altitude, T_L = 5 (the maximum value for T_L)

$$T = \left[\frac{3000 - \Delta A_{terrain}}{3000\ \text{feet}}\right] X \left[\frac{5.0}{1.0 + \left(\frac{\Delta L_{terrain}}{3.0\ \text{miles}}\right)}\right]$$

If ownship position is within the terrain, i.e. altitude is within terrain height and lateral position is within the terrain, T = 25 (the maximum value for T)

Weather Risk (W)

$\Delta A_{weather} = \text{ownship altitude - weather height}$

If $\Delta A_{weather}$ > 3000, W = 0

If $\Delta A_{weather}$ < 0, W_A = 5 (the maximum value for W_A)

$\Delta L_{weather}$ = ownship latitude – weather latitude

Weather latitude is defined by the outer ring of the weather system

If ownship position is within the outer edge of the weather, $W_L = 5$ (the maximum value for W_L)

$$W = \left[\frac{3000 - \Delta A_{weather}}{3000\text{ feet}}\right] X \left[\frac{5.0}{1.0 + \left(\frac{\Delta L_{weather}}{3.0\text{ miles}}\right)}\right]$$

If ownship position is within the weather, i.e. altitude is within weather height and lateral position is within the outer ring of the weather, W = 25 (the maximum value for W)

If ownship lateral position is within a red or dark red weather ring, W is multiplied by a coefficient of 1.0

If ownship lateral position is between an orange and red weather ring, W is multiplied by a coefficient of .80

If ownship lateral position is between a yellow and orange weather ring, W is multiplied by a coefficient of .70

If ownship lateral position is between an dark green and yellow weather ring, W is multiplied by a coefficient of .60

If ownship lateral position is between an orange and red weather ring, W is multiplied by a coefficient of .80

If ownship lateral position is between a light green and dark green weather ring, W is multiplied by a coefficient of .50

If the ownship lateral position lies beyond the outer ring of a weather system, W is multiplied by a coefficient of .50

Total Risk (R)

$R = P + T + W$

Total Risk is determined at each point of movement of the ownship along the chosen flight path

Total Path Value

Value = 2(R) + Path Length