THE CONTAMINATING INFLUENCE OF DISPLAY SIZE ON FLIGHT CONTROL, RISK ASSESSMENT, AND ROUTE SELECTION

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The present experiment was designed to examine the effect of display size on distance estimates used for flight control and in assessing risk for route selection. Sixteen pilots were asked to select and fly along a route using integrated hazard and primary flight displays. Display size was manipulated by altering the physical size of a two-dimensional display and through axis compression in a three-dimensional display. Display minification resulted in poorer flight control. When the display was enlarged, pilots were found to overestimate the distance from the flight path to impending hazards and subsequently choose riskier routes. Pilots also exhibited greater confidence in their route choices with the large display, even though their choices were more dangerous. Results suggest that display size must be considered when designing displays for spatial tasks.

While recent technological advances have allowed for the presentation of information on large displays, competing pressures exist to minify displays to ensure their presence in the limited area of the cockpit. Even though display size is often manipulated to meet these pressures and constraints, little research has been done to directly examine how such changes influence estimates of distance. Distance estimation serves as a central and initial step in many flight responsibilities, including assessing the deviation of one's aircraft from an intended flight route, estimating time-to-contact in resolving conflicts with traffic aircraft, and determining how closely one will come to threatening weather systems or terrain.

In most instances in aviation, an estimate of an environmental distance (measured in miles or meters) must be made by assessing the distance as portrayed on a map or interface within the context of the *display scale.* Display scale simply represents a ratio of display units to world units (e.g., 1 cm = 5000 m), and can be manipulated in several ways. The present examination focuses on two ways of manipulating display size, namely by altering the physical size of a two-dimensional display and through axis compression along the line of sight in a three-dimensional display.

The physical size of a 2D display can be manipulated by enlarging or reducing the dimension of the display while preserving the information contained therein. Thus, when the frame of the display is enlarged, the content of the information within the display remains the same, but the size of the information changes proportionally. 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 and 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).

While 2D display physical size minification and 3D axis compression result from different sources, the degree of minification can be adjusted so that the display scale is equivalent across these methods of size manipulation. Specifically, the elevation angle of the camera in the 3D display can be adjusted so that the degree of compression in the line of sight axis is equivalent in display distance (pixels or cm) to the display scale of the minified 2D display. By equalizing the degree of minification across the methods of manipulating size, any discovered differences can be attributed to the manner in which size was manipulated (2D physical size minification or 3D axis compression), rather than the reduced resolution traditionally associated with smaller displays.

To the extent that a pilot is using a computational approach to distance estimation, in which both the display distance and display scale are computationally integrated to derive world distance, the method of size manipulation and the display scale of the different display sizes should not bias estimates. While these explicit methods of estimating distance 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 resource-intensive approach. Such an approach is likely to be based in automatic perceptual processes (Tversky & Kahneman, 1983) rather than cognition. This perceptual process is grounded in the fact that display distance is an easily *accessible* (Kahneman, 2003) source of information that can be perceived quickly and effortlessly with a simple glance to the display, and, when resources or time are limited, may be the only informational cue used in making estimates of world distance. While this approach might generally be useful, it may also cause *size contamination,* in which the size of the display influences the estimation of world distances and the resultant tasks of flight control, time-to-contact estimation, and route selection.

Research examining size contamination of distance estimates in a two-dimensional display has not been conclusive (cf., Wickens, Alexander, & Hardy, 2003; Prinzel, Kramer, Comstock, Bailey, Hughes, & Russell, 2002), though an extensive body of evidence exists to suggest that axis compression in three-dimensional displays results in an underestimation of distance along the compressed axis (Boeckman & Wickens, 2001; McGreevy & Ellis, 1986; Yeh & Silverstein, 1992). While this evidence suggests that display size can contaminate judgments of distance, the present study asks how these biases will be manifest in flight control and spatial decision making tasks, both of which are important resultants of distance estimation.

Flight Control

While optimally a pilot should adapt flight control in response to manipulations of display size, research indicates that size contaminates performance, whether size is manipulated by altering physical size (Abbott & Moen, Comstock, Jones, & Pope, 2003) or through axis compression (Boeckman & Wickens, 2001). Such contamination may result from two separate sources, namely resolution or urgency. Under a *resolution* model, poor flight control with minified displays will result because these displays portray the smallest deviations too minutely to be noticed. Since pilots are unable to detect these below-threshold deviations, they exhibit no control activity and the deviation goes uncorrected.

Under an *urgency* model, however, poorer flight control results with small displays because pilots perceive the smaller displayed error as indicative of smaller world error. Thus, deviations are corrected less aggressively. As urgency manifests itself in the allocation of attentional resources, it should be more malleable to display and task differences. While initial research by Muthard and Wickens (in press) suggests that urgency is the driving force of size contamination, that study examined only a simple tracking task. The present study seeks to examine the role of resolution and urgency in a more realistic and complex flight simulation, coupling flight control with route selection.

Route Selection

Assessing the risk associated with potential flight plans relies upon an estimate of distance from ownship to hazards along the flight path. Consequently, biases in distance estimation may result in size contamination in route selection. For example, a pilot may estimate the distance between ownship and a hazardous mountain as larger (safer) when presented on a large display.

When translating these estimates of risk to route selection, we can predict a *preference reversal* in path selection 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 could estimate that the hazards are a sufficient distance from the shorter route, choosing instead to continue on the route despite its potential compromise of safety. No prior literature was found that examined the influence of 2D physical display minification or 3D axis compression on risk assessment and route selection.

The present study was designed to examine the presence of size contamination on distance estimates used in flight control and route selection. Participants were presented with an integrated hazard display that depicted two flight routes, one of which was more efficient. Pilots were asked to select a route that optimized efficiency while preserving safety and then travel along the selected route. Participants also made distance and time-to-contact judgments in response to presented probes. Display size was manipulated by altering the physical display size (2D) and through axis compression (3D).

METHODS

Participants

Participants were 16 aviation students who ranged in age from 18 to 32 years (M = 19.9). Thirteen participants had their private piloting licenses, while the remaining three participants had student licenses.

Displays

The display consisted of an integrated hazard display (IHD) panel that depicted terrain, weather, traffic aircraft, and the two flight paths. The primary flight display (PFD), was located directly above the IHD and presented ownship, a lead aircraft, and the flight paths from a track-up top-down viewpoint and a side viewpoint. The size of the displays was manipulated by altering the physical display dimensions or through axis compression. When physical size was manipulated (2D displays), the small display measured 8 by 6 cm, while the large display measured 29 by 22 cm. When size was manipulated through axis compression (3D), the view along the line of sight represented the small axis while the axis orthogonal to the line of sight represented the large axis. The degree of axis compression was defined such that the compressed axis was equal in display length to the small axis in the 2D display and the expanded axis was equal to the large axis in the 2D display. The 2D and 3D displays are shown in Figures 1 and 2, respectively.

Route Safety

The safety of the two presented routes was quantitatively defined by a risk algorithm, 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. 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.

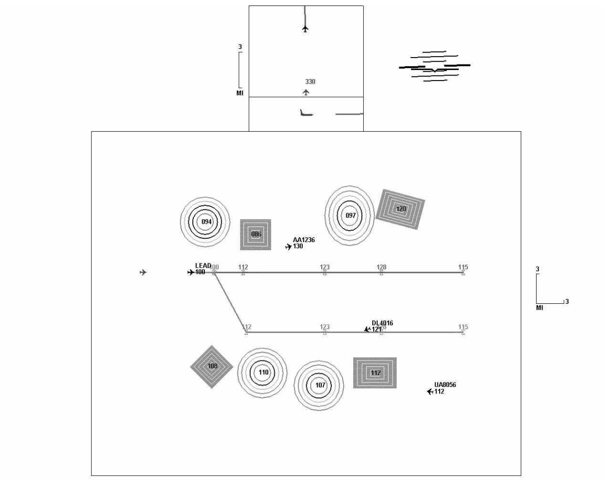

Figure 1. 2D display depicting integrated hazard display in the lower panel and a primary flight display in the upper panel.

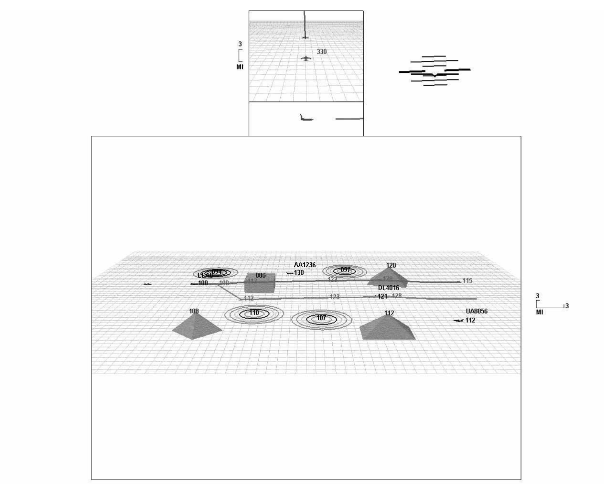

Figure 2. 3D display depicting integrated hazard display and primary flight display. Note that the compressed axis was always the depth axis in the display, while the lateral axis remained uncompressed.

The trials were constructed such that one path, the *efficient route* was always the shorter of the two routes. The second path, the *diversion route*, was significantly longer, but was designed to divert around some potential hazard. The risk of the efficient route and diversion route were manipulated to produce three path conditions. In the *safe* condition, the efficient route (risk = 30) was safer than the diversion route (risk = 45). In the *unsafe* condition, the risk of the efficient route was elevated (risk =45), while the risk of the diversion route was lowered (risk = 30). In the final condition, the *very unsafe* condition, the risk of the efficient route was maximized (risk = 60), while the risk of the diversion route was maintained (risk = 30). Note that as the three conditions progressed, the risk of the efficient route increased linearly.

Procedure

Within 30 s of the start of the trial, participants selected a flight route with a key press and then rated the safety of each flight path and using a Likert scale ranging from "very unsafe" to "very safe". A similar scale was used to rate confidence in path selection. Pilots were then asked to fly along the selected route and to maintain a five mile separation from a lead aircraft using the primary flight display coupled with a two-axis joystick with throttle. A three mile scale was presented to the left of the primary flight display window to assess in the miles-in-trail tracking judgment. To assess more explicit distance estimates, every 30 s after the initial path selection, pilots were asked to estimate the distance to or time-to-contact between two hazards on the IHD. In making this estimation, pilots were provided with a scale for the display (see Figures 1 and 2) and entered the estimate on a keyboard. Probes were designed such that estimates were required in both the east-west direction and the north-south direction. Thus, in the 3D display, these estimates were made along the noncompressed and the compressed axes, respectively. Pilots participated in one practice trial and 18 experimental trials. Display dimensionality and display size were manipulated and counterbalanced in a within-subjects design.

RESULTS

Distance and Time-to-Contact Estimation

Error for both time and distance estimates were assessed separately for the 2D and 3D displays as a function of display size in a repeated measures ANOVA. Display size, manipulated through a reduction of 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, indicating that ample time was available to use a more analytic approach to estimation.

Time was underestimated in all conditions by an average 37.2 s. While time estimates were also unaffected by 2D physical size ($p > 0.10$), 3D axis compression caused pilots to underestimate time-to-contact to a greater degree for estimates made along the compressed depth axis (48.8 s) relative to the noncompressed lateral axis (37.0 s) ($t(14) = 3.9$, $p = 0.001$). 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.

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. For the 2D display, flight control error for the miles-in-trail axis was significantly higher than the lateral and vertical axes ($F(2, 30) = 173.3$, $p < 0.001$). Analyses revealed a decrement in flight control performance with display minification for all three 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 less than the reduction of display size (72%).

Analyses for the 3D display also indicated that control for the compressed axis was poorer than that for the expanded axes ($F(1, 15) = 191.17$, $p < 0.001$). Because this difference in the 3D display is confounded by the difference in lateral tracking with miles-in-trail tracking, the latter of which was found to be significantly poorer in the 2D display, the effect of axis compression on flight control was further evaluated by comparing the ratio of error from lateral tracking to miles-in-trail tracking with 3D compression with that of 2D size reduction. This analysis revealed a 33% increase in the ratio of lateral tracking to miles-in-trail tracking from the 2D display to the 3D display ($F(2, 30) = 3.76$, $p = 0.03$), confirming that the reduction in tracking performance within the 3D display was due to axis compression. The decrement due to axis compression, after controlling for the difference in flight control performance for the miles-in-trail axis, was found to reach a 158% increase in tracking error.

Route Selection

While route preference was assessed with a Chi-squared analysis, subjective ratings of route safety and selection confidence were assessed separately for the 2D and 3D displays as a function of display size and path condition in repeated-measures ANOVAs. Subjective ratings of planned path safety were found to significantly decrease as a function of the algorithmic ratings of efficient path safety ($F(2, 30) = 7.7$, $p = 0.002$), thus validating the general efficacy of the safety measure as well as the pilots' sensitivity to the differences in safety levels of the presented flight paths.

Further 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).

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. As shown in Figure 3, 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 short path was unsafe, however, 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 ($X^2 = 8.1$, $p = 0.006$).

Figure 3. Percentage of trials in which pilots selected the efficient route as a function of path safety and axis compression.

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 evidence for the role of accessibility of display distance in implicit distance estimates.

In the final measure of route selection performance, pilots were more confident when selecting routes presented with a large display format ($F(1, 15) = 15.2$, $p = 0.001$). This finding was somewhat enhanced when size was manipulated through axis compression, as evidenced in the marginally significant interaction of display dimensionality and size ($F(1, 15) = 3.0$, $p = 0.10$).

DISCUSSION

The present experiment was designed to provide an overarching examination of the effects of display size, manipulated by changing 2D physical display size or through axis compression in a 3D display, on implicit 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 for more explicit estimates.

Analyses revealed little evidence 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 accurate, computational approach. Time-to-contact estimates, however, were reliant on more complex mentally integrated judgments of time and speed, and were thus biased in the predicted direction by axis compression. Thus, when explicit judgments of distance are required, the judgments are object and unbiased by display size. When distance is assessed implicitly, as a vehicle for calculating time-to-contact, the display size contamination is manifest.

Contamination was also found to extend to implicit distance estimates used in both flight control and route selection. Replicating findings from the literature (Abbott & Moen, 1981; Barfield et al., 1995; Boeckman & Wickens, 2001; Comstock et al., 2003; McGreevy & Ellis, 1986; Muthard & Wickens, in press), a reduction in display size was found to produce an increase in flight control error, regardless of how size was manipulated. The degree of contamination, however, was much greater when the displays were reduced through 3D axis compression (158% error increase), relative to 2D physical size minification (41% error increase). Since the resolution of the small displays was equated across dimensionalities, this effect reduces the likelihood that the reduction in flight control performance was due to resolution. Rather, it is likely that reduced display scale produced less *urgency* in deviation correction.

While display minification reduced flight control performance, display magnification produced inflated estimates of route safety. Thus, pilots estimated the span between ownship's projected location and an impending hazard as larger, and thus safer, when the distance was portrayed in a larger display scale, regardless of how size was manipulated. These findings provide additional support for the hypothesis that display distance information is used without fully considering display scale, likely because of the accessibility (Kahneman, 2003) of the displayed information. While these biased estimates did not influence route selection when 2D physical size was manipulated, they did contaminate confidence and route choice in the 3D display. In particular, pilots selected more conservative routes when the distance between ownship and the hazards were presented along the compressed axis. Conversely, when this same span was presented in a noncompressed form, the distance was overestimated, leading pilots to select riskier routes and to do so more confidently. This increase in confidence with larger display scales likely reflects the greater resolution of the displayed information, which pilots perceived as more accurate.

Conclusions

Display size, manipulated through 2D display minification or through 3D axis compression, influenced implicit distance estimates used in flight control, time-to-contact estimation, risk assessment, and route selection. For these tasks, estimates were found to be contaminated by the accessibility of display distance information in extrapolating world distance. Thus, while display magnification led to greater estimates of path deviation and more urgent flight control, as well as reduced the tendency toward underestimation of time-to-contact, it also caused overestimation in the assessment of the span between a pilot's own aircraft and an impending hazard. The presented results suggest strong caution should be taken in manipulating display size, either through changes to physical size or through axis compression, without fully considering the resulting effects on performance and flight safety.

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