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AN EXAMINATION OF THE EFFECTS OF DISPLAY ENLARGEMENT ON FLIGHT CONTROL

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The present experiment was designed to assess the effect of display size on flight control within the framework of three proposed hypotheses: the ecological, resolution, and urgency hypotheses. Sixteen pilots completed a basic flight control task under single and dual axis control. Display size was manipulated by altering the physical dimensions of a two-dimensional display and through the compression of the axis along the line of sight in a three-dimensional display. Pilots exhibited less path error and greater stick activity with a large-scale display, regardless of display dimensionality and task load, suggesting that larger depictions of error lead to greater urgency in correcting deviations. The effect was modulated by compression means (2D vs. 3D). Practical implications of these results are that caution should be taken when minifying displays to fit within cramped cockpits, as such changes may hinder flight control.

Technological advances are creating competing pressures to both minimize aircraft displays, to preserve their presence in the cockpit, and to create full-scale representations of the world (Prinzel, Comstock, Glaab, Kramer, and Arthur, 2004). It is unclear, however, how such changes in display size will affect flight control and judgments of flight path deviation. Oftentimes, such deviation or distance judgments are reliant upon an estimation of the distance in the world (e.g., meters or miles) through an examination of the distance as it is depicted on a display (e.g. centimeters). This can be accomplished by assessing the displayed distance between the intended flight path or a hazard and ownship's true location and dividing that value by the display scale. This relationship can be described as a ratio of display units, such as display pixels or centimeters, to world units, such as meters or nautical miles. The display-units to world-units ratio can be manipulated through four different means, as shown in Figure 1. In the top two panels of Figure 1, the world is represented on the left and the display manipulation is depicted on the right.

The primary way that this ratio may be varied, is through a manipulation of the **physical size** of the display (Figure 1a). Thus, when a display is minified or enlarged, the display-to-world-units ratio will decrease or increase respectively, to the extent that the information contained within each display does not vary. When this information *does* vary within a display, (e.g. by zooming in or out on a region of the airspace) but the size of the display itself does not change, the differences in the geometric field of view (Figure 1b), will produce changes in the ratio. Displays with a large geometric field of view will depict a greater portion of the airspace, but this information will be presented in a smaller scale, while those with a smaller geometric field of view will present a "zoomed in" perspective. Figure 1c presents the differences that can occur when the size of the display remains the same, but the distance from which the display is viewed is altered, thus changing the magnitude of the visual angle of the display. These three display formats can be applied to two-dimensional displays, whereas the final method of altering size is inherent only in three-dimensional displays.

The final means by which the display-units-to-world-units ratio is modified is through **axis compression** (Figure 1d). While 3D displays allow for a more natural depiction of the world, representing the space on a 2D surface results in the compression of at least two of the display axes (Boeckman and Wickens, 2001), thus depicting the world distance with fewer display pixels and a smaller display visual angle (Boyer and Wickens, 1994). Such compression increases as the viewing plane is rotated to approach the line of sight and decreases to zero when this plane is orthogonal to the line of sight (Barfield, Hendrix, and Bjorneseth, 1995). As

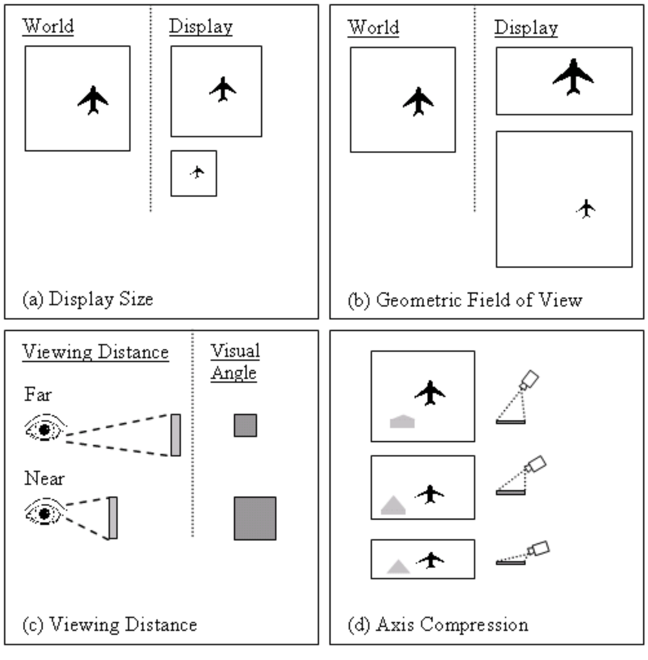

Figure 1. Differences in display size due to (a) physical size, (b) geometric field of view, (c) viewing distance, and (d) the compression of an axis in three-dimensional displays. In (d) the compressed axis (here the depth axis) is represented by fewer display units and a smaller visual angle than the uncompressed (here the lateral axis) axis.

compression of a given axis increases, the resolution of that axis is reduced (Boeckman and Wickens, 2001), and consequently the display-to-world-units ratio is also reduced. Thus, varying the physical size of the display, the geometric field of view, the viewing distance, or presenting a 3D world on a 2D surface will create variations in the ratio of display units to world units.

The present study is designed to examine how changes in the display-units to world-units ratio, either through variations in physical size of a display (Figure 1a) or the compression of an axis along the line of sight in a 3D display (Figure 1d), affects deviation estimation and tracking. Our research examines three possible hypotheses regarding how the pilot tracks dynamic systems with different ratios of display to world units. The **ecological hypothesis** posits that pilots will account for differences in display scale, regardless of the means through which the differences are rendered, thus tracking the aircraft as it exists in the world (the ecology) and producing no performance differences across display size. The ecological hypothesis, therefore, represents an optimal pilot. In support of the ecological model, Comstock, Glaab, Prinzel, and Elliot (2001) demonstrated that tracking error did not differ as a function of physical display size in a synthetic vision display of terrain information. Despite these findings, a large body of literature exists to suggest that tracking performance *is* contaminated by size. The most concrete example of physical size contamination is reflected in a study by Comstock, Jones, and Pope (2003), who presented participants with an attitude indicator display, used to depict the aircraft's pitch and bank relative to the horizon, in sizes ranging from 1 to 12 inches wide. These researchers found that flight control error was the highest for the smallest display and that performance continued to improve with display enlargements. Researchers have also shown that size contamination exists when the display-units to world-units ratio is varied through axis compression along the line of sight in a 3D display. For example, observers have been found to underestimate differences on a compressed axis in 3D displays (see Wickens, 2002), thus leading to degradation of tracking performance. Two possible sources of contamination can be explained by the resolution and urgency hypotheses.

The **resolution hypothesis** posits that, with smaller displays, the most minified deviations will be sub-threshold and will not be noticed or corrected. The **urgency hypothesis**, however, suggests that for all deviations, the pilot will perceive smaller display units as smaller errors. Larger display units, however, will be seen as larger errors and will thus be corrected with more urgent control movements. This hypothesis has been developed in a model of multi-axis tracking by Onstott (1976). It is also inherent in the crossover model of manual control (McRuer and Jex, 1967; Wickens and Hollands, 2000), which assumes that within a given display, larger errors are corrected with more aggressive (higher velocity) control action. Thus, both the resolution and urgency hypotheses would predict greater errors with decreasing size, though this effect would be less pronounced under the resolution hypothesis, as it only applies to the perception of near-threshold errors.

The urgency hypothesis suggests that tracking performance is cognitively-based and is thus more highly influenced by task and display differences. In dual axis tracking tasks, this hypothesis would posit that increased urgency to one task should be associated with the allocation of resources to that task, relative to a less urgently perceived (i.e., smaller display units) axis. Under this hypothesis, tracking should also be considerably more malleable (than under resolution) to variations in the cause of display differences (e.g., the different panels in Figure 1). The resolution hypothesis, however, predicts tracking performance to be uninfluenced by how scale differences are created, because the effect of display size is purely a sensory one.

Empirical data on the effects of size on tracking behavior and performance is relatively sparse and ambiguous. Consistent with the urgency hypothesis, Abbott and Moen (1981) found that pilots maintained more accurate spacing intervals behind a lead aircraft when a cockpit traffic display was increased in size. Comstock et al. (2003) found a similar result, showing that an enlargement in the physical size of an attitude directional indicator resulted in superior flight control. In contrast, Alexander, Wickens, and Hardy (2003) found an influence of scale (see field of view in Figure 1b) on tracking performance that was opposite to the urgency hypothesis, showing that larger scale produced greater error. Prinzel et al. (2004), as well as Comstock et al. (2001), however, reported no effect of display size. Finally, Haskell and Wickens (1993) and Wickens, Liang, Prevett, and Olmos (1996) found in multi-axis flight simulations, that pilots showed greater tracking error in a compressed axis within a 3D display.

The objective of the present study was to examine the relative contribution of the mechanisms postulated in the 3 hypotheses (ecological, resolution, and urgency) to tracking performance, as display size is varied via the physical size and axis compression, in single task conditions, as well as in dual task conditions, when resources were scarce and therefore might be allocated differentially between axes as suggested by the urgency hypothesis. Under the assumptions of the ecological hypothesis, we would expect to find no differences in tracking with variations in display size, as the operator would account for the differential depictions of world units. Under the resolution hypothesis, we should expect to find that performance is degraded with smaller display sizes and the degradation is constant across the 2D display and 3D display. If, however, the magnitude of the small size tracking error decrement is fully equal to the difference in display size, if the performance decrement is amplified under dual axis control, or if size manipulations differentially affect performance with the 2D relative to the 3D displays, then these differences would support the urgency hypothesis, which argues that smaller displays lead to perceptions of less error and thus less urgency to correct the deviation.

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. All participants were right-handed.

Displays

The 2D display (Figure 2) depicted a vertical and a horizontal axis in two separate panels that were separated by 17 degrees of visual angle. The cross in the center of each panel represented the target location for each axis. The sizes of the scales were varied to be small or large, such that the central cross encompassed two degrees (2 cm) or 4 degrees (4 cm) of visual angle, respectively. A scale and tick marks, shown along the edges of each panel, were used to denote distance from the target point within each display panel. The 3D display (Figure 3) depicted both the horizontal and depth axes in a single, integrated panel. As the target, designed to represent the pilot's aircraft moved further away in depth, the cursor would become smaller in size, thus producing a realistic sense of three-dimensionality in space. While physical size was not explicitly manipulated, the depth axis, presented along the individual's line of sight, was smaller due to the compression associated with representing a three dimensional world in only two dimensions. It is important to note that the degree of axis compression in the depth axis of the 3D display was equal to the degree of size reduction in the 2D display. In other words, the display-units to world-units ratio was consistent across display dimensionalities.

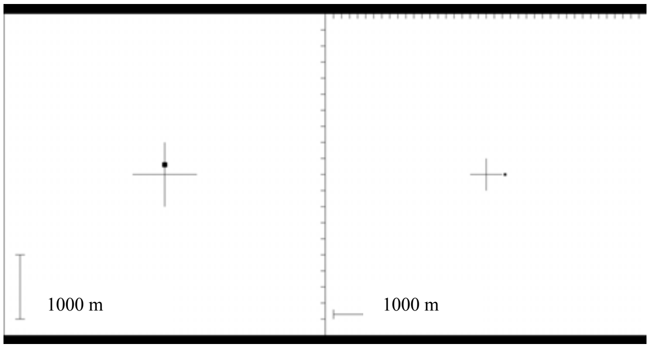

Figure 2. Two-dimensional flight control display. The vertical axis was always presented on the left, while the horizontal axis was always presented on the right. In the above example, the vertical axis was presented in the large scale, with the horizontal axis depicted with the small display scale. Scales were present in the lower left-hand corner to depict the display distance to world distance ratio.

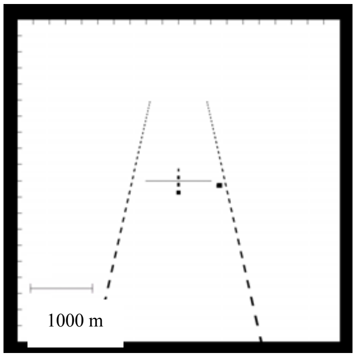

Figure 3. Three-dimensional flight control display. The depth and horizontal axes were presented in a single-panel integrated display. The depth axis was always the compressed axis, while the horizontal axis was expanded. The converging dashed lines are provided to induce the sense of depth and three-dimensionality.

Task

Participants completed a first-order, single or dual-axis compensatory tracking task using the 2D or 3D display. When using the 2D display, participants were asked to control either the vertical or horizontal axis alone, or the two axes simultaneously. Participants performed single-axis control, with the 2D display, by using the single joystick responsible for controlling the axis. For the vertical axis in the 2D display, forward stick movement led to downward movement of the cursor, as would be the case for an attitude directional indicator. For the depth axis in the 3D display, forward stick movement caused the cursor to move further away in distance or higher in the visual plane. Under dual axis control with the 2D display, two joysticks were used to control the two axes.

With the 3D display, participants were asked to control the depth or horizontal axis alone, or the two axes simultaneously. As the 3D display was integrated in a single panel, so was control, such that participants performed single axis and dual axis control with the use of only one joystick.

The two axes in each condition were driven by independent quasi-random disturbance inputs (sum 3 sine waves) with a bandwidth of 0.6 Hz. In all trials, participants were asked to maintain a minimum deviation of 500 m, thus they were tracking *world units*, as opposed to *display units*. Participants completed a practice trial with both the 2D and 3D displays and nine experimental trials, which each lasted two minutes. Display dimensionality, axis size, and task load (number of axes controlled) were manipulated and counterbalanced in a within-subjects design.

RESULTS

A repeated-measures, 2 (dimensionality) x 2 (axis size) x 2 (task load) ANOVA was conducted on both the RMS error and stick velocity data. Figures 4 and 5 present the tracking error and control activity data for both the 2D and 3D displays, as a function of display size. In each figure, the predicted findings for the ecological (E) and urgency (U) models are also plotted. As shown in the figures, there was 8% and 27% greater error for the smaller display with both 2D and 3D displays, respectively ($F_{(1, 15)} = 30.7$, $p < 0.001$; $F_{(1, 15)} = 39.0$, $p < 0.001$, respectively). The display-units to world-units ratio then did, at least to some extent, contaminate the estimation of world error, as well as impacted the pilots' subsequent control responses. Analyses examining control activity mirrored the control error findings, exhibiting a 8% and 33% reduction in stick velocity with display minification in the 2D and 3D displays, respectively ($F_{(1, 15)} = 22.7$, $p < 0.001$ for 2D; $F_{(1, 15)} = 67.8$, $p < 0.001$ for 3D). Collectively, these results suggest that the ecological model alone is not sufficient to explain the results.

Recall that the urgency model, which predicts that error will decrease and control activity will increase with display enlargements, posits that pilots attend more to display distance information than to the world distance that must be estimated. Thus, under extreme predictions of the urgency model, changes to error and stick velocity should be proportional to the degree of enlargement in the display (or the degree of enlargement in the display-units to world-units ratio). While the data indicated that display size did contaminate deviation distance judgments, the difference was relatively small (a ratio of small to large of 1.0:1.2 or 235m:274m) compared to the ratio of display sizes (1.0:2.0 or 2cm:4cm), as seen by comparing the slope of the dashed line (U) with those of the empirical data in Figure 4. This suggests that the extreme urgency model may not provide a sufficient lone source of interpretation of the data.

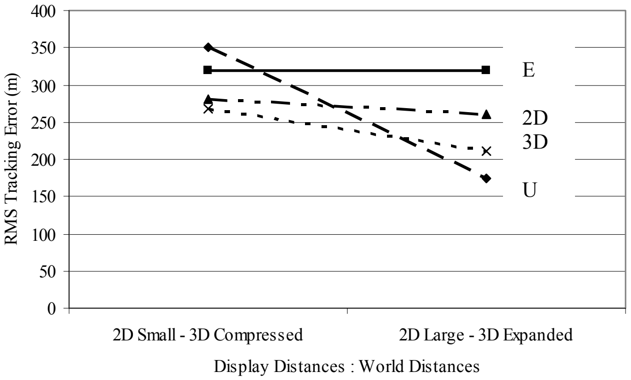

Figure 4. RMS tracking error as a function of axis compression and display dimension. The light solid and dashed lines are the error differences that would be predicted under the pure ecological (E) and urgency (U) hypotheses, respectively. Note that the difference in error under urgency is a 2:1 ratio, associated with the ratio of size differences employed.

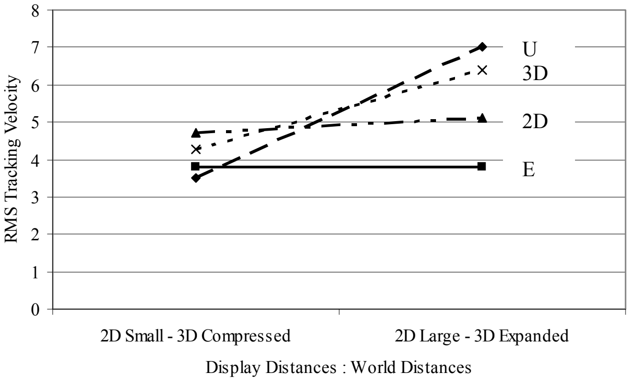

Figure 5. Control activity as a function of axis compression and display dimension. The light solid and dashed lines are the velocity differences that would be predicted under the pure ecological and urgency hypotheses, respectively. Note that the difference in velocity under urgency is a 2:1 ratio, associated with the ratio of size differences employed.

While the ratio of error in the small to large display was smaller than that predicted by pure urgency model, additional analyses were conducted to suggest that urgency may underlie the mechanisms involved in size contamination. The differences in the size effects for the 2D and 3D displays, supported by a significant dimensionality X size interaction ($F_{(1, 15)} = 9.8$, $p = 0.007$) suggested that a size reduction due to axis compression within the 3D display created a greater increase in error, than did the reduction of the same magnitude within the 2D display, which can be seen by comparing the slopes of the two empirical lines in Figure 4, as well as in Figure 5. Thus, the small axes in the 2D display were equal in display distance (2 cm) to the compressed axis, while the large axes in the 3D display were equal in display distance (4 cm) to the non-compressed horizontal axis, though the size effect on error was more pronounced in the 3D display. Therefore, the results suggest that display distance was not the sole contributing factor to the increase in control error found with smaller displays, but that additional factors, such as user strategies or perceptual biases associated with 3D displays were affecting control behavior, thus providing support for some contribution of the urgency hypothesis. Support for urgency was reflected to an even greater extent in the significant interaction between dimensionality and size in control activity ($F_{1, 15)} = 41.92$, $p < 0.001$), with a larger effect of size for the 3D than for the 2D display (Figure 5).

Finally, to the extent that the allocation of effort, associated with "urgency," is a resource limited process, we might expect a greater effect of size in dual axis tracking when resources were at a premium than in single axis tracking when they were less so. Surprisingly, this finding was not confirmed. Task load (single vs. dual axis control), while significant ($F_{(1, 15)} = 66.4$, $p < 0.001$), and while interacting significantly with display dimensionality ($F_{(1, 15)} = 80.7$, $p < 0.001$; greater dual axis cost in 2D than 3D), did not interact with size; either in the 2 way interaction, or in the 3 way size X dimensionality X load interaction ($p > 0.10$ for all analyses). Note that we attribute the greater dual axis cost in the 2D display to the benefits of display and control integration in the 3D display (Fracker and Wickens, 1989).

DISCUSSION AND CONCLUSIONS

Three models were proposed to predict the influence that the distance-units to world-units ratio, manipulated either by varying the physical size of the display or through compressing the display axis that was parallel to the line of sight, might have on flight path deviation estimation and flight control. The ecological model posited that pilots are equally successful in flight tracking across different display sizes, thus accounting for differences in the distance-units to world-units ratio created by manipulations of display size and axis compression. Analyses revealed that tracking became inferior when information was presented on displays with a small display-units to world-units ratio, thus eliminating the applicability of the pure ecological hypothesis, while lending support for the contributions of the resolution and urgency models.

The resolution and urgency models posited that tracking error should be poorer for displays with a reduced display-units to world-units ratio, because deviations depicted with these displays are sub-threshold or because small display units are perceived as smaller world unit deviations, respectively. Specifically, the evidence suggested that participants experienced less urgency to correct deviations in displays with a small display-units to world-units ratio, particularly when minification was accomplished through axis compression in the 3D display. As the display-units to world-units ratio was equal across dimensionalities, the results suggest that the manner in which this ratio is manipulated (either through physical size or through axis compression in a 3D display), has a direct influence on subjective urgency to correct the two axes within each condition.

While these data serve to provide some support for the urgency hypothesis, the reduction in error and increases in control activity with larger display units were small relative to the increases in display size, suggesting that effects of urgency were modest. The lack of interaction of size with task load, which should have reflected an amplification of the urgency effect with increasing resource demands, provides additional support to the finding that urgency may only play a moderate role on flight control.

In conclusion, the presented results suggest that display size can have important effects on the performance of certain spatial tasks, such as flight control, and that both display minification and 3D axis compression can have degrading effects on performance, though the effect was modest. It is important to note that the small display used here, which encompassed only two degrees of visual angle (2 cm), is approximately the same size as the back-up attitude indicator, suggesting that findings reported here may be generalized to instruments currently located in the cockpit and that even small manipulations to display size can serve to influence flight control performance in significant ways.

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