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EFFECTS OF PREVIEW, PREDICTION, FRAME OF REFERENCE, AND DISPLAY GAIN IN TUNNEL-IN-THE-SKY DISPLAYS

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ABSTRACT

This study investigates theoretical explanations for the benefit of improved flight-path tracking in tunnel-in-the-sky displays when compared to conventional instrumentation. Pilots flew flight paths in a computer simulation with a manipulation of visual display characteristics. The variables of prediction, frame of reference, and preview were contrasted in a fully factorial design. Results support the idea that prediction and frame of reference provide the largest contribution to the tunnel-in-the-sky display benefit. Prediction had little effect on performance and display gain did not account for the frame of reference effect.

INTRODUCTION

The tunnel-in-the-sky display depicts a pilot's flight path on a computerized display. These displays have received a lot of investigation and critical acclaim in recent years. There has been considerable research illustrating the benefit of the tunnel-in-the-sky display concept for flight-path tracking when compared to conventional flight instrumentation (e.g. Haskell & Wickens, 1993; Alter & Powell, 1999; Ververs & Wickens, 2000, Wickens, Haskell & Harte, 1989; Jensen, 1981; Beringer, 1999), but little research has investigated the reasons behind the benefit specifically.

The tunnel-in-the-sky contains a number of characteristics that may account for this benefit. While some properties of the tunnel have been previously explored such as dimensionality (Haskell & Wickens, 1993) and symmetry (Theunissen, 1997), other explanations have not been as well investigated. Among these characteristics are the elements of preview, prediction, frame of reference, and display gain (See Figure 1.)

Preview

Tunnel-in-the-sky displays contain the element of preview in which future command path information is presented to the pilot and shows where the pilot should be. For example, in Figure 1, the tunnel may be seen curving to the left. This property may account for the tunnel-in-the-sky benefit by allowing the pilot to anticipate for upcoming demands and prepare a response prior to reaching the turn. This anticipation is not possible in systems that do not contain preview.

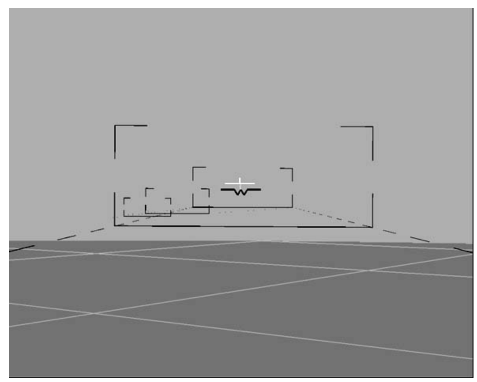

Figure 1. A sample tunnel-in-the-sky display showing elements of preview, prediction (the white aircraft), and an egocentric frame of reference.

Prediction

Prediction refers to the extrapolation of the current position to some distance or time into the future, given no further action by the pilot. In Figure 1, prediction is shown as the white aircraft symbol just beyond the black boresight (the aircraft's current position). This symbol indicates to the pilot that, given no further input, they will be at that position within seconds. Prediction may account for the benefit of the tunnel by providing feedback to pilot on the basis of their actions. This reduces the amount of mental computation of future position needed by the pilot, something that requires cognitive effort.

Notice that both prediction and preview allow for the pilot to anticipate upcoming events in the real world. Preview allows the pilot to anticipate upcoming command inputs (where they should be) while prediction allows the pilot to anticipate the results of their actions (where they will be). However, while both of these may contribute to the tunnel-in-the-sky benefit, the characteristic of prediction has been traditionally paired with preview so the individual benefit of each characteristic cannot be determined within the tunnel-in-the-sky context.

Frame of Reference

The operator's frame of reference may also play a role in describing the tunnel's benefit. Egocentric and exocentric viewpoints anchor two ends of a continuum. Immersed viewpoints are considered to be egocentric in which the viewpoint in the display corresponds to the viewpoint of the observer as if they were immersed within the scene (as in Figure 1). The alternate is an exocentric displays in which the viewpoint is extracted from the scene. Tunnel displays typically demonstrate better flight path tracking performance than exocentric displays (Wickens & Prevett, 1995; Olmos, Wickens, & Chudy, 2000).

This effect may be due to ambiguity in altitude information with an elevated exocentric viewpoint. When the viewpoint is immersed in the display, as with an egocentric viewpoint, lateral and vertical dimensions in the display are preserved. In an exocentric display, when the viewpoint is extracted, the viewpoint is no longer positioned directly behind the controlled element and distortions occur on the basis of the displacement of the viewpoint. Lateral displacement of the viewpoint results in lateral distortions and vertical displacement results in vertical (altitude) distortions with a larger displacement creating a larger distortion. Thus displays that contain an egocentric viewpoint (like the tunnel-in-the-sky) preserve the visual relationships for tracking performance.

Display Gain

A confound to the egocentric frame of reference explanation is the fact that there is a greater change in the information displayed in an egocentric display compared to an exocentric display for the same real world event. This display change is called display gain and may account for the frame of reference benefit by suggesting that the immersed viewpoint is not the tunnel element that enhances performance but rather that pilots may be more aggressive in correcting for flight-path deviations if those deviations are reflected by larger changes in the display.

Overview

The tunnel-in-the-sky display contains a number of display elements that may contribute to the benefit of flight path tracking that is seen with the tunnel-in-the-sky display. What has not been addressed is the relative benefit of each of these explanations to account for the benefit found in tunnel-in-the-sky displays for flight-path tracking. The purpose of this study was to contrast these explanations to determine the relative benefits of each display characteristic.

METHODS

Subjects

The subjects for this experiment were 24 student pilots with an average of 150 hours of flight time, ranging from 110 hours to 225 hours. All subjects were paid for their participation. All subjects had normal or corrected vision.

Apparatus

The experiment was conducted in a computer based flight simulation. A Silicon Graphics IRIS Elan computer generated the visual displays, controlled flight dynamics, and collected data. Manual input was generated via an IBM PC AT through an analog input, serial connection. Manual input was limited to a 90-degree bank to the right or left.

Design

Three independent variables of preview, prediction, and frame of reference were contrasted in a 2x2x2 full factorial design. One additional condition to investigate display gain was also included. Preview was contrasted in a between-subjects manipulation of presence of tunnel or absence of tunnel. The variable of prediction was a within-subjects variable that was varied with prediction or without prediction. The variable of frame of reference was a within-subjects variable and varied at an egocentric viewpoint or exocentric viewpoint. The exocentric viewpoint was pulled back and offset by a vertical angle of 10 degrees looking downward on the aircraft. Examples of different manipulations of the variables of interest are shown in Figure 2. The display gain condition looked exactly like Figure 1 but was reduced in size so that the display gain was equivalent to the same display with an exocentric viewpoint. The dependent measures were lateral and altitude root mean square error from the center of the flight path.

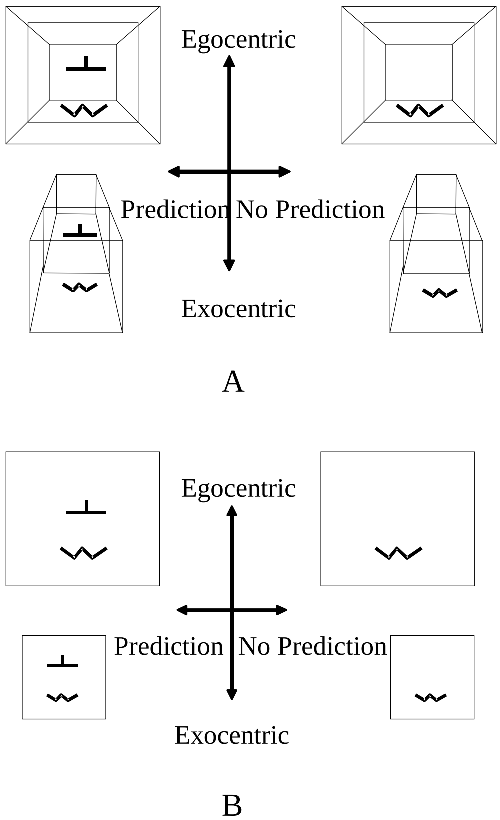

Figure 2. A schematic representation of experiment displays featuring preview (tunnel), prediction, and frame of reference variables. A. Tunnel displays. B. No Tunnel displays.

Procedure

Pilots were first assigned to either the preview or no preview condition and matched in number of flight hours between the two conditions. Pilots were instructed to keep as close to the center of the flight path as possible. Each pilot saw a total of 72 different flight paths during the course of the experiment that contained between 9 to 14 legs to the path. Consecutive legs that changed in course heading and/or altitude at each leg in the flight.

Each pilot was tested over two sessions on the simulation. The first session contained series of 12 practice trials that gave pilots a chance to become familiar with the simulator and the displays being used. Following practice, pilots saw two blocks of 12 trials each. Each block contained one of the four experiment displays (egocentric-prediction; egocentric-no prediction; exocentric-prediction; exocentric-no prediction) for the preview group they were in (tunnel or no tunnel).

Pilots returned for a second session within two days of the original session. In the second session, all pilots first saw a 12-trial block of the display gain condition, followed by two blocks of 12 trials of the two displays not yet completed.

RESULTS

An analysis of variance (ANOVA) was performed on both the lateral and altitude data for the three primary variables of interest. A log transform was performed on the altitude data because the untransformed data showed a high degree of skew. The lateral data did not show this skew and were not transformed.

In the graphs below, data points contain standard error bars. Data points have been enlarged for perceptual clarity and may obscure the standard error bars.

Altitude Deviations

Figure 3 depicts the effects of the independent variables on the transformed altitude data. In this analysis a main effect of preview was significant [$F(1,22) = 13.04$, $p<0.01$] and its effects can be seen within the significant frame of reference by preview interaction [$F(1,22) = 23.29$, $p<0.01$] in which the tunnel provided a benefit to vertical performance in the egocentric display (left side of figure 3) that was absent in the exocentric display (right side of figure 3).

There was also a main effect of frame of reference in the altitude data [$F(1,22) = 108.36$, $p<0.01$] in which the egocentric frame of reference showed smaller altitude deviations than did the exocentric conditions.

There was no main effect of prediction [$F(1,22) = 0.13$, $p=0.72$], interaction of prediction with frame of reference [$F(1,22) = 1.15$, $p=0.30$], nor three-way interaction [$F(1,22) = 0.35$, $p=0.56$].

While there was no interaction of prediction with preview [$F(1,22) = 1.54$, $p=0.23$], the trend in the exocentric data and the inherent display ambiguity in the exocentric display suggested a closer look. In analyzing just the exocentric data (shown on the right side of figure 3), a significant interaction of prediction by preview was revealed [$F(1,22) = 7.65$, $p=0.01$]. This showed that the presence of prediction reduced altitude error when the tunnel was present and increased error when the tunnel was absent, in comparison to the conditions that did not contain prediction.

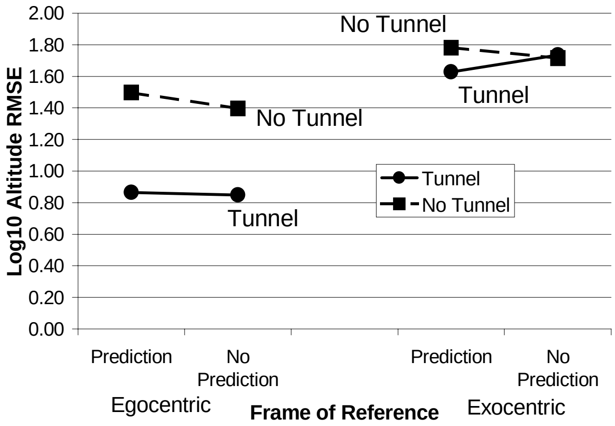

Figure 3. Log10 transformation of the altitude root mean square error data as a function of frame of reference, prediction, and preview.

Lateral Deviations

Figure 4 graphically depicts the results from the ANOVA on the lateral data. As with the lateral data, a main effect of frame of reference can be seen [F (1,22) = 77.99, p<0.01] in which lateral deviations are reduced by an egocentric frame of reference. A main effect of preview was also found [F (1,22) = 137.63, p<0.01] in which the tunnel reduced lateral deviations compared to conditions without the tunnel.

The interaction of preview with frame of reference was also significant [F (1,22) = 41.14, p<0.01]. The egocentric viewpoint reduced the benefit of the tunnel compared to the exocentric condition.

There was a small but consistent benefit of prediction [F (1,22) = 7.54, p=0.01] in which the presence of prediction enhanced performance compared to conditions without prediction for lateral deviations. There was no preview by prediction interaction [F (1,22) = 0.07, p=0.79], prediction by frame of reference interaction [F (1,22) = 2.13, p=0.16] or three-way interaction [F (1,22) = 0.39, p=0.54].

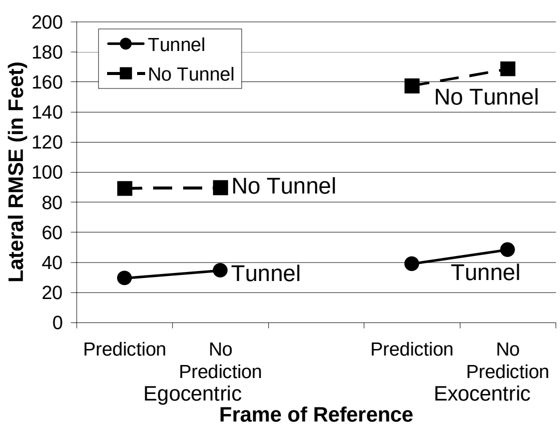

Figure 4. Lateral root mean square error data as a function of frame of reference, prediction, and preview.

Display Gain

Four t-tests were generated to compare the effects of display gain separately from those of frame of reference. The reduced gain condition was compared for both lateral and altitude data against both the egocentric-tunnel-prediction condition (to which it was perceptually equivalent) and the exocentric-tunnel-prediction condition (that it was equivalent to in display gain). The results of these comparisons are depicted in Figure 5.

There was a small increase (2 feet) in altitude error when the reduced gain condition was compared against the egocentric display condition [t=-2.67, p<0.01]. This suggests that there was some cost to the reduced gain independent from the egocentric frame of reference. When the reduced gain condition was compared against the exocentric display condition, the difference in means was significant [t=4.71, p<0.01]. The effect size in this case, however, was 48 feet different that suggests that the exocentric frame of reference cost is due to the viewpoint location rather than to its reduced gain effects.

In the lateral error data, a difference in means between the egocentric frame of reference and the reduced gain condition again showed a difference [t=4.71, p<0.01]. The effect size between these conditions was seven feet in the direction of the display gain condition. The comparison between the reduced gain condition and the display gain condition was also significant [t=6.17, p<0.01] in which the reduced gain condition showed a 16 foot reduction in lateral deviations when compared to the exocentric display condition. As with vertical error, this difference also shows that the exocentric frame of reference cost is not due to reduced gain, but rather due to the viewpoint location.

DISCUSSION

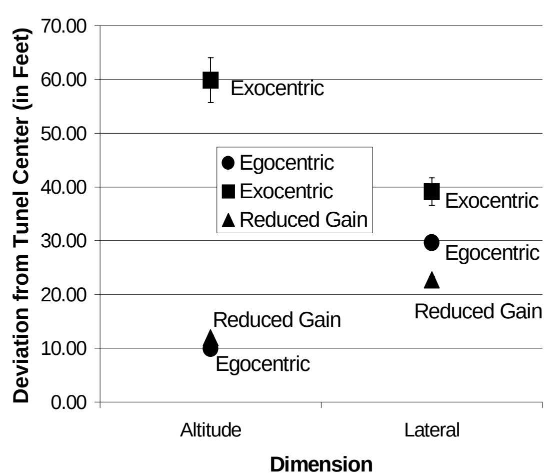

Figure 5. Lateral and vertical deviations from tunnel center as a function of reduced gain conditions and control comparison conditions.

A number of conclusions may be drawn from these data. It is clear that preview makes a large contribution to the tunnel-in-the-sky display benefit. The effects of preview can be seen in both the lateral and vertical data. While this is not a new finding (e.g. Jensen, 1981; Haskell & Wickens, 1993; Ververs & Wickens, 2000) this effect is typically confounded with the effects of prediction. This study has demonstrated a clear effect of preview in the tunnel, independent of prediction.

Given the expected benefit of prediction, it is puzzling that so little effect of prediction was observed. Two explanations may be offered. First, prediction is typically investigated in conjunction with preview and therefore this may be a true representation of the effects of prediction within a tunnel-in-the-sky context. Second, the benefits of prediction may be realized when feedback on pilot input is delayed or lagged. This is when feedback about future position on the basis of current input would be most important. The current simulation was created to mimic the dynamics of a small aircraft in which the feedback from input is relatively fast. Thus it may be the case that the benefits of prediction were not needed for this simulation.

A clear benefit for frame of reference was seen in this data. This is also not a new finding (Olmos, Wickens, & Chudy, 2000; Wickens & Prevett, 1995) but this data helps to suggest a reason for this benefit. This reason may be most clearly seen in the frame of reference by preview interaction for vertical tracking. The presence of the tunnel reveals a benefit with the egocentric display that does not occur in the exocentric display. However, for lateral tracking, the tunnel shows a benefit for both egocentric and exocentric displays. Notice that there are no altitude ambiguities created by the egocentric viewpoint, nor by the exocentric viewpoint in the lateral dimension because there was no lateral offset for the exocentric viewpoint but a vertical offset was present. This argument of vertical ambiguity is consistent with the data in that the lack of a tunnel benefit in the exocentric display is most likely due to the viewpoint vertical offset. Stated in other terms, when there is an offset angle, there is ambiguity in the exocentric viewpoint and when there is ambiguity, the tunnel fails to offer benefits.

The relevance of vertical ambiguity is further suggested by the preview by prediction interaction in the altitude data for the exocentric displays as seen in the right side of figure 3. In this data, an interaction was seen in which the presence of the exocentric tunnel reduced altitude deviations, but increased them when the tunnel was absent. This suggests that both prediction and preview are needed to help resolve the ambiguity created by the exocentric view with an angular offset.

It is interesting to note that the display gain manipulation demonstrated that the frame of reference benefit was solely due to viewpoint location alone, and not due to the increased gain present in the display. This suggests that it is the viewpoint location that enhances the pilot's performance rather than creating a more aggressive error-correcting strategy.

To summarize, three conclusions may be drawn from this data. First, the relative effects of these variables suggest that preview and frame of reference (immersed viewpoint) provide the largest contribution to the tunnel benefit for flight path tracking while prediction generates a much smaller contribution. Second, the role of perceptual ambiguity appears to play a large role in the exocentric frame of reference cost in the altitude data. Even the inclusion of preview through the presence of the tunnel did not reduce this cost. Finally, it is clear that the frame of reference contribution to the tunnel benefit is due to the immersed viewpoint characteristic of the tunnel rather than the increased display gain. Taken together, all of these results demonstrate the effectiveness of the tunnel-in-the-sky as a display concept for flight-path guidance and begins to explain the underlying reasons behind the tunnel-in-the-sky benefit.

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