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THE EFFECTS OF SPATIAL AWARENESS BIASES ON MANEUVER CHOICE IN A COCKPIT DISPLAY OF TRAFFIC INFORMATION

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Two experiments exploring the design of the Cockpit Display of Traffic Information (CDTI) for traffic avoidance maneuvers were conducted. Thirty-six certified flight instructors from the University of Illinois Institute of Aviation flew a sequence of flight scenarios to compare the effects of traffic load, dimensionality, and a vertical situation display (VSD) orientation (rear view vs. side view) on maneuver choice. The display modulation of general maneuver tendencies was examined in terms of spatial awareness biases. Against the backdrop of a preference for vertical maneuvers, spatial constraints within each display type invited different maneuver preferences according to qualitatively different ways in which the format of spatial information rendering biased or distorted information interpretation.

Introduction

Spatial constraints within display types can invite different pilot maneuver preferences according to qualitatively different ways in which the format of spatial information rendering may bias or distort information interpretation. The focus of the current study is on how representing the three dimensionality of airspace on either a 2D coplanar or 3D perspective Cockpit Display of Traffic Information (CDTI) influences maneuver choice.

The 2D coplanar display contains a top-down view of the flight environment in the top panel, as well as either a rear-view or side-view depiction in the bottom panel, or the vertical situation display (VSD). More precise spatial and relative position judgments are best made using a 2D coplanar display due to its unambiguous depiction of the three dimensional airspace (St. John, Smallman, Bank, & Cowen, 2001; Wickens, 2000). In particular, the vertical dimension represented within the VSD allows for a precise rendering of the effects of vertical maneuvering. Despite these performance advantages, the 2D coplanar display imposes a visual scanning cost due to the presentation of lateral and vertical information on two different display panels. This scanning/information access cost is further amplified to the extent that information must be integrated across the two panels depending on the task at hand (Wickens, Merwin, & Lin, 1994), as implied by the proximity compatibility principle (Wickens & Carswell, 1995). As we shall see, the integration of vertical and longitudinal (along flight path) information in a single panel may be advantageous for vertical maneuvering.

While 3D displays have been supported due to their "natural", integrated representation of the 3D world, costs in terms of biases and distortions are inherent. Namely, the **"2D-3D effect"** leads pilots to subjectively rotate vectors in depth more parallel to the viewing plane (McGreevy & Ellis, 1986). This effect may be manifest as biases in the following three ways. First, observers have a tendency to perceive a slanted surface as being more parallel to the viewing plane than it really is—the **"slant underestimation effect"** (Perrone & Wenderoth, 1993). Second, the **compression effect** describes how at least two of three axes must be compressed to display a 3D world on a 2D screen. Increased compression is associated with a reduction in resolution which will lead to a bias in estimating distances along the compressed axis as shorter than they really are (Boeckman & Wickens, 2001). Third, the **line-of-sight ambiguity effect** degrades relative and absolute knowledge of positions as less linear information is available (McGreevy & Ellis, 1986). As we will see, some of these effects may bias pilots' perception of location, thereby influencing their maneuver choice.

Table 1 provides a summary of the types of traffic avoidance maneuvers chosen by pilots across a number of studies. In general, initial testing of maneuvering in a free flight environment using a planar CDTI revealed a tendency for pilots to prefer resolving conflicts by maneuvering vertically (Abbott et al., 1980). Maneuvering within the vertical plane, however, conflicts with how pilots are instructed to maneuver under visual flight conditions according to current Federal Aviation Regulations (FAR, 91.113). The FAR instructs pilots to make lateral maneuvers in avoiding traffic due to an inherent inability to determine the altitude of other aircraft. Altitude information provided by a CDTI, however, allows pilots to identify the initial altitude of conflicting aircraft and choose a vertical avoidance maneuver accordingly.

The finding of a vertical preference in conflict avoidance maneuvers has been replicated several times since the Abbott et al. study (see Table 1). Helleberg, Wickens, and Xu (2000) summarize three related explanations for why vertical maneuvers are chosen over prescribed lateral maneuvers. First, vertical maneuvers result in smaller deviations from the intended flight path and are therefore more efficient in terms of returning to the intended path after the conflict has been resolved (Krozel & Peters, 1997). Second, lateral maneuvers are third order control tasks while vertical maneuvers are second order and hence are of less cognitive complexity (Wickens, 1986; Wickens & Hollands, 2000). Finally, because vertical maneuvers take less time to implement, because of their lower order, they are more effective under high time pressure.

The current paper describes results from two experiments that bear on the influence of format on choice—more details of each experiment are provided in Alexander and Wickens (2001, 2002).

Method

Thirty-six certified flight instructors (experience, M = 833 flight hours, M = 164 instrument flight hours) from the University of Illinois Institute of Aviation flew a sequence of flight scenarios, across two experiments, designed to compare the three formats of the CDTI. The experiment was conducted on a low fidelity personal computer flight simulator with a flight stick controlling pitch, roll, and throttle.

Displays

The CDTI presented ownship and traffic, each with 45-second predictor lines. Symbology developed by Merwin, Wickens, and O'Brien (1997) was employed to graphically present information regarding the degree of conflict and time until the loss of separation with any traffic aircraft converging on ownship. This loss of separation was defined as penetration of a cylindrical protected zone around ownship, 1500 feet above and below and 3 miles in radius.

Coplanar Formats. The coplanar display shown in Figures 1a and b consisted of two windows offering a horizontal, top-down (X-Z axes) view and either a vertical, forward-looking (X-Y axes) or vertical, side-looking (Y-Z axes) VSD projected orthogonally (without perspective information). Both VSDs contained two sets of horizontal lines indicating the altitude boundaries of ownship's protected zone.

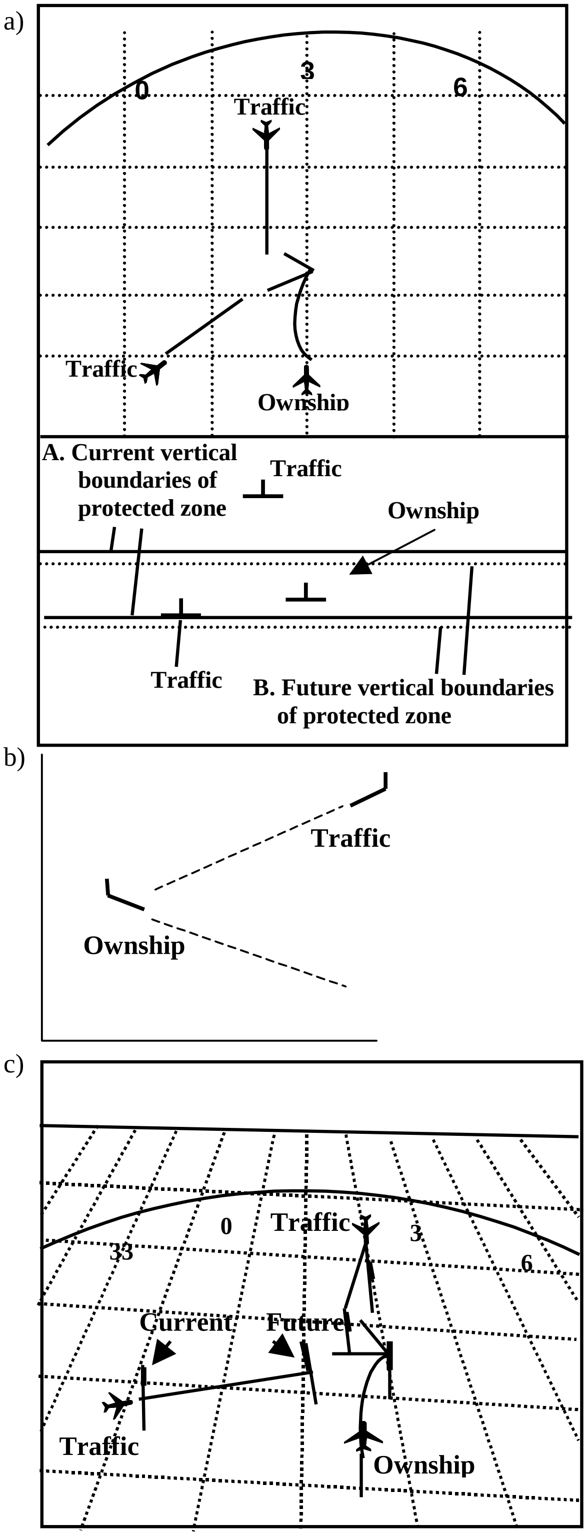

Figure 1. Three display versions of the CDTI: (a) 2D coplanar rear-view, (b) 2D coplanar side-view, (c) 3D. The rendering of the side view profile in (b) is not what participants actually saw, but is a schematic designed to highlight the different orientation of the VSD from figure (a).

*3D Format***.** The 3D display shown in Figure 1c depicted an integrated view of the airspace from a perspective above and behind ownship, with an elevation angle of 45°, and an azimuth offset of 10°. The display showed the previously described symbology along with droplines to unambiguously show the horizontal positions of the aircraft icons and the ends of the predictive lines.

Task & Design

Pilots flew direct routes to predetermined waypoints while encountering other aircraft, and maneuvered to avoid conflicts with traffic, while minimizing deviations in speed, heading, and altitude from target values. After determining that the conflict had been resolved, the pilot returned to the flight path to intercept the waypoint.

Display type was manipulated by providing the three viewpoints (Figure 1). Traffic level was manipulated by including 2, 6, or 10 aircraft besides ownship in the first experiment, and 2, 4, or 6 aircraft besides ownship with 1, 2, or 3 predicted conflicts, respectively, in the second experiment.

Pilots performed two replications of the 9 trials in counterbalanced order, formed by the 3x3 combination of traffic load (low, medium, high) and display format.

Results

Maneuvers were categorized according to timelines created from the raw data as lateral, descents, climbs, airspeed, lateral/vertical, and airspeed/vertical based on the pilot's control inputs and flight parameters for each trial. Figure 3 presents the pooled data of both experiments.

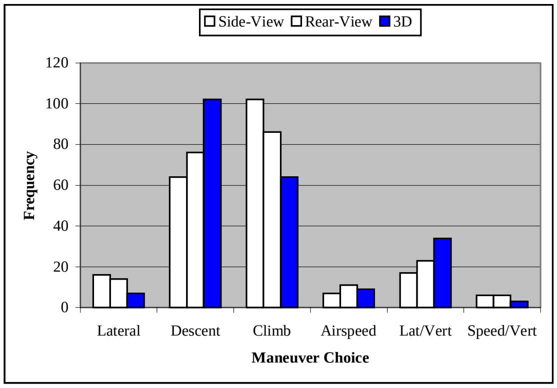

Figure 3. Maneuver frequencies by display type.

The figure illustrates the clear dominance of vertical over other maneuvers, χ^2 (1, $\underline{N}$ = 647) = 179.7, $\underline{p}$ < .01, as well as a preference for climbs over descents for the coplanar side-view display, χ^2 (1, $\underline{N}$ = 166) = 8.70, $\underline{p}$ < .01 and a preference for descents over climbs for the 3D display, χ^2 (1, $\underline{N}$ = 166) = 8.70, $\underline{p}$ < .01.

We inferred from the finding of a strong vertical preference within the coplanar displays that the linear representation of the VSD invited a greater number of vertical than lateral maneuvers. In particular, the side-view display invited a greater number of climbs than descents, a preference which may be considered "safe" in light of the dynamics involved with vertical maneuvering. Essentially, when a pilot initiates a descending maneuver, airspeed naturally increases. Therefore, if a descending maneuver is selected incorrectly and the pilot fails or forgets to compensate for the natural airspeed increase by throttling back, the time until a conflict will be reached will decrease and the pilot will have less time to correct the maneuver. The side-view coplanar display, in particular, most clearly represents this inherent danger of descending maneuvers through its integrated vertical and longitudinal depiction of the flight path within a single panel, and therefore invites a greater number of the "safer" climbs than the more risky descents.

Our hypothesis for the inherently "unsafe" 3D descent preference was that ownship could be perceived to be lower than the traffic ahead (even if it was not) in the 3D display, so pilots were more likely to descend. As described in the introduction, 3D displays impose a bias such that the natural depth cue of "height-in-the-plane" is underestimated in its impact due to the slant underestimation effect, and is not seen to fully reflect the distance of the traffic ahead of ownship, but also, to some extent, the true height above the ground. For example, while ownship and the traffic ahead of ownship are at the same true altitude in Figure 1c, ownship, being lower in the visual field, would be biased to be perceived at a lower altitude. Such a bias would lead pilots to overestimate the altitude of aircraft ahead of ownship and therefore bias maneuver choices to fly under traffic at the same altitude. According to such an argument, the descent tendency would be enhanced as the number of traffic ahead of ownship increased.

The above argument was supported by the data in Figure 4 (extracted from only the second experiment) which presents the proportion of descents chosen as a function of the proportion of aircraft located ahead of ownship. The graph illustrates that the proportion of descents did in fact generally increase as the proportion of traffic ahead of ownship increased.

Overall, the number of descent maneuvers chosen was doubled from the smallest to largest categories of aircraft located ahead of ownship.

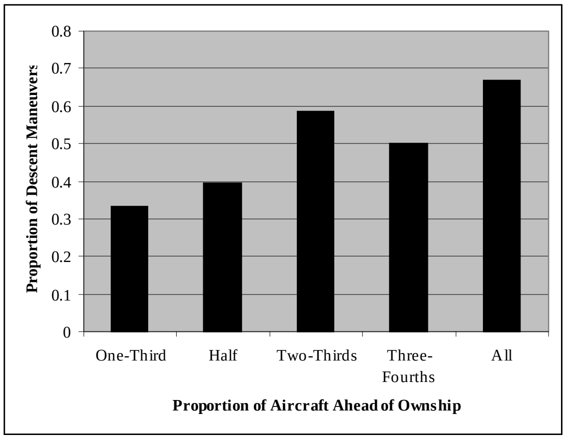

Figure 4. Proportion of descents by proportion of aircraft located ahead of ownship on the 3D display.

Discussion

The display modulation of general maneuver tendencies was examined in terms of spatial awareness biases. Spatial constraints within each display type invited different maneuver preferences according to qualitatively different ways in which the format of spatial information rendering biased or distorted information interpretation.

First, the same traffic geometry information was presented in such a way that it was either easy or difficult to access. For the 2D coplanar display, the vertical dimension was represented in a clear, unambiguous fashion, therefore inviting a greater number of vertical than lateral maneuvers. Within these vertical maneuvers, it appeared that the flight path representation of the VSD influenced the tendency to climb versus descend, as indicated by the climb preference within the side-view display.

Second, we infer that the "2D-3D" effect (McGreevy & Ellis, 1986) led pilots to subjectively rotate vectors (i.e., between ownship and traffic) in depth more parallel to the image plane than they were in the real world, as a result of rendering a 3D space on a 2D image plane. In the context of an overwhelming preference for vertical maneuvers, the 3D display increased the frequency of descent maneuvers relative to climbs. This descent preference was attributed to the perceptual bias to perceive distant traffic (at ownship's altitude) as higher than it truly was, a manifestation of the "2D-3D" effect known as the "slant underestimation effect" (Perrone & Wenderoth, 1993). The 3D preference for descending maneuvers may invite a greater potential for conflicts when considering that descending maneuvers naturally increase airspeed. As previously discussed, if a descending maneuver is selected incorrectly, the time until a conflict will be reached will thereby decrease and the pilot will have less time to correct the maneuver. Both coplanar views eliminated the descent preference, and in particular, the side-view display induced a "safer" climb preference due to the integrated vertical representation associated with this display, relative to that with the 3D display.

Conclusions

In conclusion, differences or changes in display format may have two separate effects on pilot information: (1) They may invite or inhibit certain types of maneuvers by making certain features of the airspace more or less salient (e.g. side-view climb preference due to its longitudinal depiction of the flight path); (2) They may influence the quality of the chosen maneuver, by distorting the nature of certain information (e.g. the slant underestimation effect inducing a descent preference with the 3D display). These modulations in choice preference are added atop an overall predisposition to maneuver vertically, as apparently driven by the joint influences of efficiency and complexity.

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Table 1. Summary of maneuver frequencies. + = Most preferred. 0 = Less preferred. - = Least preferred. NA = Not available/reported. Partially adapted from Helleberg, Wickens, and Xu (2000).

Experiment	Lateral	Vertical	Airspeed	Multi-axis	Remarks
Beringer (1978)	+ (pilots prefer R) (non-pilots L)	**NA**	**NA**	**NA**	Visual only static display No CDTI
Abbott, Moen, Person, Keyser, Yenni, & Garren (1980)	-	+	**NA**	**NA**	Advanced research aircraft 2 nm X 1000 ft
Palmer (1983)	+	**0** (preferred under time pressure)	**NA**	-	High fidelity Comm. Transport 2D 1.5 nm X 500 ft
Chapell & Palmer (1983)	-	**0**	+	**NA**	High fidelity GA 2D 2.0 nm X 500 ft
Smith, Ellis, & Lee (1984)	+ (turn toward)	-	**NA**	**0**	Low fidelity Comm. Transport 2D
Ellis, McGreevy, & Hitchcock (1987)	+ (2D more than 3D)	**0** (3D more than 2D)	**NA**	-	High fidelity Comm. Transport 2D and 3D 3 nm X 1000 ft
Merwin & Wickens (1996)	**0** (3D more than 2D) (R turn toward)	+ (2D more than 3D) (2D opposite dir.)	**NA**	-	Low fidelity Comm. Transport 2D and 3D 3 nm X 1000 ft
O'Brien & Wickens (1997)	- (turn toward)	+ (3D more than 2D) (2D climb)	**NA**	**0** (2D more than 3D)	Low fidelity Comm. Transport 2D 3nm X 1500 ft weather hazard
Wickens & Morphew (1997)	**0** (symbology affected)	+	-	**NA**	Low fidelity Comm. Transport 2D 3 nm X 1500 ft monitoring task
Gempler & Wickens (1998)	-	+	**0**	**NA**	Low fidelity Comm. Transport 2D 3 nm X 1500 ft monitoring task
Wickens & Helleberg (1999)	**0**	+	**0**	-	Low fidelity Comm. Transport 2D and 3D 3 nm X 1000 ft weather hazard
Helleberg, Wickens, & Xu (2000)	**0**	+	**0**	-	High fidelity Comm. Transport 2D 1.5 nm X 1000 ft outside visual world
Alexander & Wickens (2001)	**0**	+ (2D climb) (3D descent)	-	**0**	Low fidelity Comm. Transport 2D rear-view, side-view, and 3D 3 nm X 1500 ft
Alexander & Wickens (2002)	**0**	+ (3D descent)	-	**0**	Low fidelity Comm. Transport 2D rear-view, side-view, and 3D 3 nm X 1500 ft