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COMPARING TUNNEL-IN-THE-SKY DISPLAY ON HDD AND HUD FROM TASK OCCUPATION POINT OF VIEW

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A series of flight simulations was carried out to investigate the causal factors of attention capture, focusing on a traffic detection task while following a curved trajectory using a Tunnel-in-the-Sky display. The location (head-up or head-down) and size of the display were varied, and traffic detection time and path tracking performance were measured. The results show that the HUD gave the best path tracking at the expense of traffic detection performance, and supports the hypothesis that using a limited viewing volume and high display gain with a Tunnel-in-the-Sky display induces pilots to rely on precise guidance cues instead of the “tunnel” itself, consequently focusing much attention on the control task.

Since the concept of instrument flight was introduced a half-century ago, there have been a number of efforts to develop a display that provides visual cues as intuitive as out-of-window visual cues. A perspective image of a nominal flight trajectory is a typical concept for such a display. In spite of the fact that several such displays have been developed with different names—Channel (Kanal)-, Corridor-, Highway-, Pathway- and Tunnel-in-the-Sky Display—these all share the same basic idea and concept.

The advantages of the Tunnel-in-the-Sky over conventional 2D display formats are reported to be (1) higher tracking performance in manual flight, (2) lower workload, (3) enhanced situation awareness, and (4) greater suitability for curved trajectories. A number of prominent research activities during the past 30 years have led to display design strategies becoming almost established (Grunwald, 1984, Mulder, 1999, and Newman, 2003). Improvements in on-board graphics generation capability and the spread of satellite navigation systems has led to a recent surge in the flight evaluation of such displays, and a few commercial products for general aviation have now appeared on the market. However, although the Tunnel-in-the-Sky has become a common image in near-future advanced cockpits, there are still several issues to be clarified before it can play a dominant role in commercial transport aircraft instrumentation. The most widely recognized of these issues is “Attention” or “Cognitive Capture”.

Many studies have investigated attention capture and path tracking performance issues with a variety of display design parameters (Fischer *et al.*, 1980, Wickens *et al.*, 1998, 2003, and Ververs *et al.*, 1998), primarily for flight path guided HUDs (Head-Up Display) but also for Tunnel-in-the-Sky displays. When a HUD is used for precision approach and landing in low visibility conditions, the display presentation should be conformal irrespective of whether conventional flight path cues or a Tunnel-in-the-Sky are depicted. On the other hand, if a Tunnel-in-the-Sky is used in visual (composite) flight, a conformal presentation may be not necessary, and the symbology may be presented on either a HUD or an HDD (Head-Down Display). In such operations, path tracking performance requirements could be relaxed compared with the approach phase, while the ability of the pilot to spot other traffic should be the same as in conventional visual flight. The question is: What is the best combination of display parameters when using a Tunnel-in-the-Sky—conformal or non-conformal, head-up or head-down?

In this paper, we temporarily define “attention capture” to mean “the pilot task is occupied by flight control tasks without notice.” This means that if the pilot realizes that his or her attention has become “captured”, he or she can recover from the situation by intentionally modifying scanning behavior. In other words, if pilots are sufficiently trained to pay appropriate attention to each item of information, “cognitive capture” should not occur so often. On the other hand, even if a pilot can maintain a good level of optimal scanning behavior, he or she is forced to pay more attention to an instrument if it has poor readability. In this research, we refer to this phenomenon as “attention occupation”, distinguishing it from “cognitive capture”.

The initial target of this research was to clarify the causal factors of “cognitive capture” associated with Tunnel-in-the-Sky displays. However, in a preliminary experiment, while “cognitive capture” phenomena were not clearly observed in the controlled experimental environment, “attention occupation” was clearly apparent with a degree that seemed to have a close relationship with display configuration. This paper reports the results of a series

of flight simulation experiments to investigate these causal factors of “attention occupation” by varying display location and gain.

Assumptions and Hypotheses

Basically, we assume that some display design factors, which differ between the HUD and the HDD, have an affect on how a pilot divides attention between flight control and other tasks. In this research, we select traffic detection as a secondary task. There are several design parameters that might affect both flight control and secondary task performance.

Display Gain and Viewing Volume: It is well known that while a higher display gain increases path tracking performance, it may degrade the stability of the closed-loop system. A study has revealed that the display gain of the conformal HUD is too high and might result in large deviations. Regardless of whether path tracking performance is good or poor, if path error is magnified the pilot’s attention becomes largely occupied by the tracking task, and so attention given to traffic detection is reduced. On the other hand, as the display size is limited, a higher gain results in narrower “viewing volume” of the tunnel image. In general, the viewing volume of a Tunnel-in-the-Sky depicted on an HDD ranges from 60 deg to 80 deg, versus a maximum of 40 deg for a conformal HUD. It is anticipated that a narrower viewing volume reduces position awareness, and may also affect traffic detection.

Location and Focal Point: As HUD symbology is projected at infinity and does not require the pilot to go “heads-down” to scan instruments, the scanning load for a HUD may be lower than for an HDD. This may lead to a HUD giving both increased path tracking and traffic detection performance.

Symbol Overlap: Because HUD symbology is presented superimposed overlapped on the out-of-the-window scene, there is a risk that traffic may be masked by symbols. Particularly in a flight simulation environment, the brightness and color of HUD symbols cannot be well controlled.

Considering these issues, the following hypothesis were set:

1. If display gain is as high as a conformal HUD, the resulting magnification of error will capture pilot attention, and path tracking performance will improve. A reduction in viewing volume may reduce position awareness.
2. If the display focuses pilot attention on the control task, traffic detection performance will decrease.
3. The location and infinity focus of a HUD may reduce scanning load and improve traffic detection or control performance. Consequently, presenting guidance symbols on a HUD but with a reduced display size may enable pilots to pay greater attention to traffic detection while giving a similar level of path tracking performance as an HDD.

Experiment

A set of piloted flight simulations was conducted to investigate the causal factors of attention occupation by comparing HUD and HDD in a task to follow a curved flight path while looking out for traffic.

Simulation Set Up

A research simulator at the JAXA Flight Research Center was utilized. The FOV (field of view) of the out-of-window visual display for a left-seated pilot is –100 to +21 deg horizontal and 35 deg vertical, realized by three SXGA-resolution visual system channels presented by a gapless WAC (Wide Angle collimation) system. HUD symbology was overlaid on a 90% transparent gray-colored “pale” background plane placed in the visual scene as a 3D object to enhance its legibility. The simulated aircraft used the flight dynamics of a Dornier Do.228-202 twin turboprop commuter airplane. All the pilots who participated in the simulation were experienced with this type of aircraft and had actual flight experience with Tunnel-in-the-sky displays (HDD).

Traffic was presented in the visual scene five or six times per flight, one airplane at a time. After entering the scene, traffic aircraft continued flying until either the pilot pressed the microphone push-to-talk (PTT) switch or until 30 seconds had elapsed, before being removed from the scene. A marker was presented at the edge of the cockpit front window as small pink semi-transparent square subtending 2x2 deg from the pilot’s eye point. Markers were presented one at a time, and remained until either the pilot pressed the PTT switch or until 15 seconds had elapsed.

The presented position was varied between nine fixed locations on the upper, lower, left and right edges of the window.

Two types of route were prepared, each consisting of four curved and straight segments with a -4 deg approach path. Pilots were instructed to fly along the displayed trajectory paying sufficient attention to other traffic.

Display Symbology and Geometry

Figure 1 shows an image of the Tunnel-in-the-Sky presented by the HDD. Table 1 shows the basic geometry and characteristics of the Tunnel-in-the-Sky display used in the simulation.



Figure 1. HDD Symbols

Table 1. Tunnel-in-the-Sky Characteristics

Parameter	Experimental Value
Cross-section Size	100 x 100m
Frame Interface	250m
Tunnel Visual Presentation	Frame (within 0.5NM) Contour (within 4.0NM)
Flight Path Predictor	5 seconds prediction with bank angle
Horizontal Prediction	Initial response slaved to pitch attitude
Flight Path Predictor	Vertical Prediction

Experiment-1

Display Configuration

A set of flight simulations was conducted to compare four types of display including HDD and HUD, varying display size. A total of six pilots participated, and each pilot flew twice for each type of display. Figure 2 shows the display configuration for the experiment.

HDD-Normal (HDD): A Tunnel-in-the-Sky integrated with a traditional PFD (Primary Flight Display) and horizontal situation display is shown on the instrument panel.

HDD-Large (HDD-L): For comparison with HDD-Normal, the display size is enlarged and the viewing volume narrowed. This results in a display gain three times greater than the HDD-Normal display, and 20% less than the HUD-Conformal case.

HUD-Conformal (HUD-CF): The Tunnel-in-the-Sky is integrated with a traditional “primary mode” HUD format, rather than an “approach” mode format. A conventional PFD and horizontal situation display are shown on the instrument panel.

HUD-Non conformal (HUD-NC): This presents the HDD symbology overlaid on the visual scene, but smaller in size than in the HUD-CF display. The flight path symbol and artificial horizon are not conformal with the visual scene. The symbols are shown in a monochrome, with the same color as in the HUD-Conformal display. Due to the nature of this display, serious clutter occurs during the final approach phase.

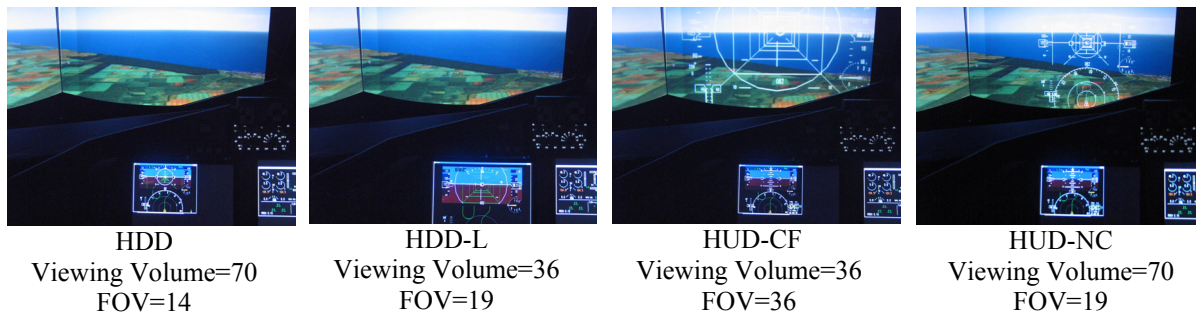


Figure 2. Display Configurations for HDD and HUD Comparison

Results

Figure 3 shows the mean RMS values of horizontal tracking error across the display types. HUD-CF and HDD-L show a significant reduction in horizontal error compared to the HDD case ($P=0.0010$, 0.0047 respectively). Figure 4 shows mean traffic detection times. HUD-CF, HDD-L and HUD-NC show significant increases in traffic detection time compared to the HDD case ($P=0.0033$, 0.0062 , 0.029 respectively). The difference between the HUD-NC and HDD-L cases is also significant ($P=0.018$). Figure 5 shows mean number of missed markers. A marker was considered as “missed” if the pilot did not push the PTT switch within 20 seconds of its appearance. HUD-CF shows a significant increase in the number of missed markers over the HDD and HUD-NC cases ($P=0.032$ and $P=0.044$ respectively).

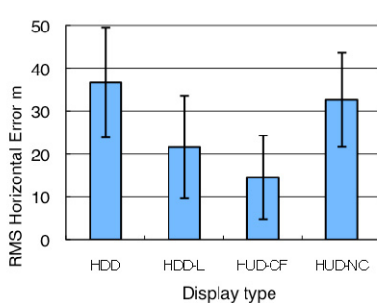


Figure 3. Horizontal Path Error

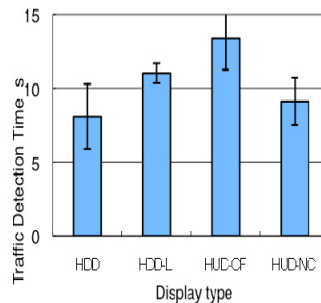


Figure 4. Traffic Detection Time

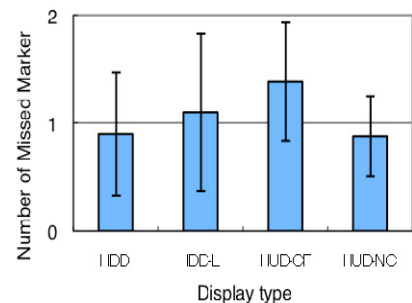


Figure 5. Missed Marker

Discussion

The lower path tracking error in the HUD-CF and HDD-L cases shows that a higher display gain enhances path tracking performance. Although most of the subjects complained of an oscillatory tendency with high display gain, they admitted that their tracking performance was better. The higher traffic detection times with these displays shows that this improved tracking performance required greater attention on the display.

Two major guidance and control cues were presented, and control behavior could be to use these in combination; i.e. tracking the target frame (“Ghost”) by the Flight Path Predictor, and navigating the ownship within the tunnel by looking at the shape of the tunnel. If precise control is required, the former cue is dominant, and the closed-loop control gain becomes higher. On the other hand, if the path tracking requirement is relaxed, as in the present experiment, the latter cue plays the major role. In this case, a pilot may adopt an “Error Neglecting Control” strategy (Tueunissen & Mulder 1995), resulting in poorer tracking performance.

In the HDD and HUD-NC cases, the subjects seemed to use an error-neglecting strategy. The observed mean horizontal error of around 35m, slightly less than half-tunnel width of 50m, supports this supposition. On the other hand, the limited viewing volume of the HUD and HDD-L displays degrades the position error information that could be perceived from the tunnel, and forces the pilots to abandon the error-neglecting strategy. Consequently, in these cases they might have to rely on the Flight Path Predictor – Ghost cue.

Some subjects complained that a narrower horizontal viewing volume limits the display of future trajectory, especially in curved flight segments. In this particular trial, subjects could not anticipate the descent point well beforehand, and this may have caused them to pay increased attention to the display.

These results can be compared with the similar previous research by Wickens (2003), who found that the higher the display gain, the poorer the tracking performance. Although Wickens’s findings appear to be completely opposite to those here, both experiments support the hypothesis that a higher display gain causes scattering of tunnel the symbols over the field of view and prevents the pilot from acquiring position information or guidance cues from the tunnel.

There is another possible explanation for attention occupation considering the effect of the “Ghost” center marker. Wickens’s “sliding box” symbol has only a square frame and lacks a center marker, while our corresponding Ghost symbol has a center marker. In the HDD and HUD-NC displays, the size of the Ghost symbol in the FOV is 5deg and 8 deg respectively, versus 20 deg for the conformal HUD. This means that the circular part of the Ghost symbol

is outside of the Useful Field of View, degrading the information it conveys. Consequently, the pilot might have had to rely on the Flight Path Predictor – Ghost (center marker) cue, and abandon the error-neglecting control strategy.

As anticipated, all subjects complained that the HUD symbology might mask traffic, or at least that they commented that they sometimes confused HUD symbol elements with traffic. This may have contributed to the longer traffic detection times observed in the HUD-CF case, but considering that HDD-L resulted in a similar traffic detection deficiency, the effect is considered to be small in comparison with the effect of viewing volume. The increased number of missed markers in the HUD-CF case also supports the hypothesis that interaction between HUD symbols and traffic is small, because the markers were presented outside of the HUD symbols.

Experiment-2

Display Configuration

An additional experiment was conducted to examine effect of display size on the trajectory tracking task. In contrast to Experiment-1, neither traffic nor markers were shown, and the subject pilots were instructed to follow the trajectory as precise as possible. The Ghost symbol was removed from the display so that the subjects had to acquire position information from the tunnel, not from guidance symbols. As shown in Figure 6, the HDD and HDD-L displays (FOV= 19deg, same as the HDD) were compared by four pilots.

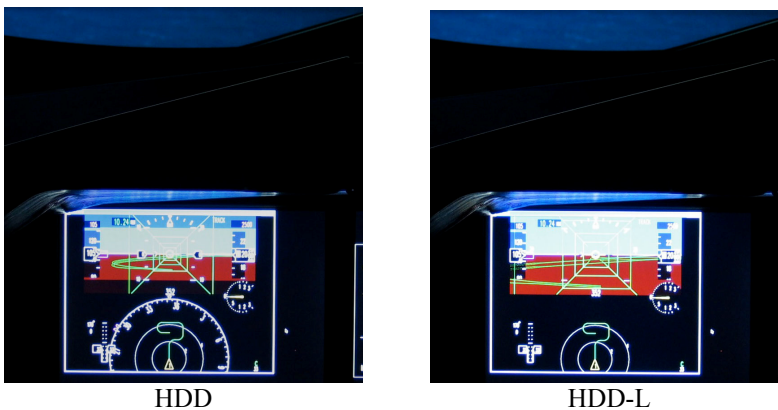


Figure 6. Display Configuration

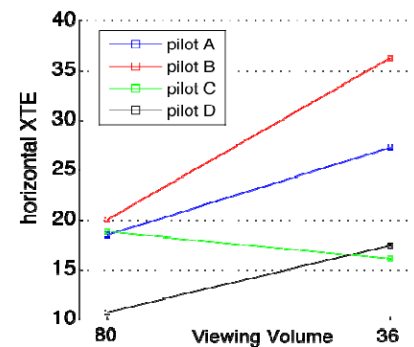


Figure 7. Horizontal Tracking Error

Results and Discussion

Figure 7 shows horizontal tracking error. Although it is not significant ($P=0.13$), three of four pilots had degraded horizontal tracking error for HDD-L, and all the pilots admitted that position awareness was degraded with the HDD-L display, especially in curved flight path sections. This result is consistent with Wickens (2003), and also supports the hypothesis that the center marker of the Ghost symbol plays major role in control strategy selection (error neglecting control or error suppressing control).

Summary and General Discussion

The results support Hypothesis 1 that high gain displays (HDD-L and HUD) give better tracking performance. However, it is considered that the observed high closed-loop gain was the result not of the high display gain but of the narrow viewing volume, which prevented pilots from adopting an error-neglecting control strategy. This view is supported by a comparison with the cases of HDD and HDD-L without the Ghost symbol, which gave opposite results to the with-Ghost cases. The center marker of the Ghost symbol, if it is present, seems to play major role on control strategy selection when display gain is high.

Hypothesis 2, that attention demanded by path tracking will reduce traffic detection performance, is supported by the result that the displays with a narrow viewing volume gave greater traffic detection times, as well as a greater number of missed peripheral markers.

The results do not support Hypothesis 3, namely that presenting guidance symbols on a HUD but with reduced display gain enables the pilot to pay optimized attention to the traffic detection while path tracking performance remains with the same as with an HDD. Although some pilots commented that the scanning load was reduced in the HUD and HUD-NC cases, no objective data were obtained. The HUD-NC display, which presents HDD symbols on the visual scene, showed almost the same tracking and traffic detection performance as the HDD, while the use of only a single color caused much clutter.

Although not detailed in this paper, there are many inconsistencies between the results of the present experiment and previous research. This indicates that attention occupation is influenced by many factors such as the subjects themselves, the detailed design of the display, types of event, and simulation fidelity. Furthermore, it should be noted that a pilot who participated in these experiments flew with a HMD with similar tunnel-in-the-sky symbols in an actual aircraft, and commented that spotting traffic through the HMD in an actual flight environment is much easier than in the simulation. Further study is strongly required.

Conclusions

This paper describes a simulation experiment to investigate the causal factors of “task occupation”, namely a situation in which “a pilot cannot pay sufficient attention to tasks other than control”, in particular dealing with traffic detection while tracking a curved trajectory. As was hypothesized, the use of a conformal HUD resulted in reduced traffic detection performance. This is considered to be caused by the reduced viewing volume of the perspective symbols of a Tunnel-in-the-Sky. A proposed non-conformal HUD showed no superiority over an HDD for detecting traffic.

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