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EFFECTS OF HEAD-UP DISPLAY AIRSPEED INDICATOR AND ALTIMETER FORMATS ON PILOT SCANNING AND ATTENTION SWITCHING

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ABSTRACT

The effects of the rotating pointers and gradation marks of head-up display (HUD) airspeed indicator (ASI) and altimeter symbology formats were examined. The effects of the gradation marks were of special interest, as being able to remove them would help reduce display clutter. The three formats examined included: rotating pointers with gradation marks, rotating pointers without gradation marks, and digits only. The pilots' eye-movement data collected during flight simulations indicated significant changes in both ASI and altimeter fixation durations between the rotating-pointer formats and digits only, but no difference between the rotating-pointer formats themselves. However, the differences between them were found in the vertical speed indicator fixations and the flight task strategies estimated by Hidden Markov Model analysis. Results provided first empirical support for the potential value of the gradation marks.

Keywords: Aircraft display; display clutter; eye movements; Hidden Markov Model (HMM).

INTRODUCTION

A head-up display (HUD) is a transparent display that provides flight information in the pilot's primary field of view, superimposed on the outside scene. The present study examined the effects of the rotating pointers and gradation marks of HUD airspeed indicator (ASI) and altimeter symbology formats. The rotating pointers are known to provide a certain degree of motion cue in peripheral vision and, by formulating expectancy of the displayed values, to facilitate quicker instrument reading (Senders, Webb, & Baker, 1955). The value of the gradation marks, however, has not been well understood. If their contribution is small, eliminating the gradation marks may become a valid option to reduce display clutter and the potential occlusion of the outside scene.

Prior to developing a military standard for HUD symbology, the US Air Force (USAF) had conducted a flight simulator study to investigate various HUD ASI/altimeter formats (Ercoline & Gillingham, 1990; Weinstein, Gillingham, & Ercoline, 1994). They found no difference between the rotating pointer formats with and without gradation marks in terms of the RMS airspeed or altitude error or subjective ratings, although both rotating-pointer formats did better than the other formats they tested, including digits-only and vertical-tape formats. The resulting military standard (MILSTD, 1996) requires the rotating pointer format to be used for ASI/altimeter symbology. The military standard also requires the gradation marks to be present, as they are still believed to provide additional advantages, despite the negative findings of the USAF study.

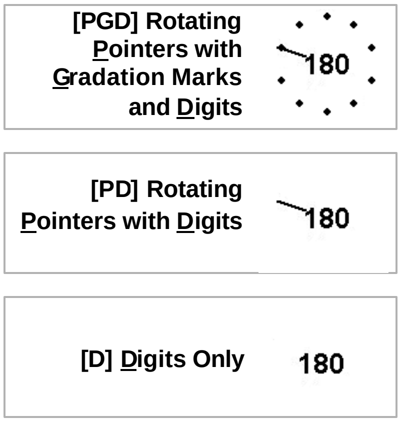


Figure 1. Three ASI/altimeter formats

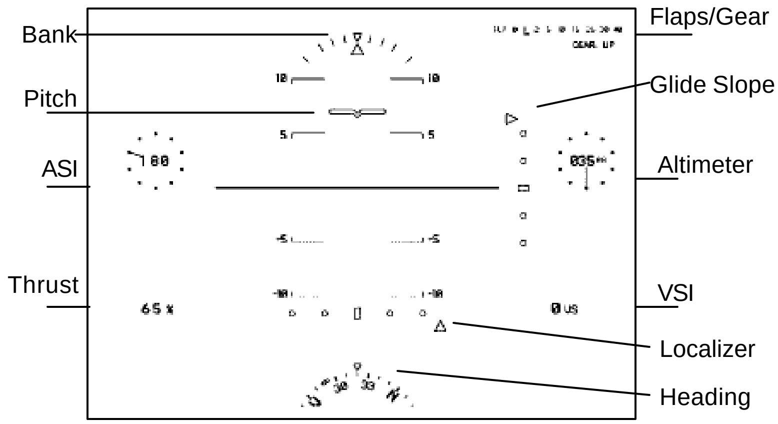


Figure 2. HUD symbology (with PGD)

The present study reinvestigated the value of the rotating pointers and the gradation marks by examining pilots' scan and attention patterns, in addition to their performance and preferences. The study was conducted as part of the effort to develop civil HUD design guidelines. Three ASI/altimeter formats similar to the ones used in the USAF study were compared (Figure 1): rotating pointers with gradation marks and digits readout (PGD), rotating pointers with digits readout but no gradation marks (PD), and digits only (D).

METHOD

Pilot Participants

Six airline transport pilots, including 3 captains and 3 first officers, participated in the study. The pilots' total flight time as of the date of the experiment ranged from 4000 to 17500 hours. One of the captains had previous experience flying approaches with HUD-equipped aircraft.

Flight Simulation

A fixed-base flight simulator configured with Boeing 737-400 flight dynamics was used. The HUD symbology (Figure 2) was projected on a screen approximately 180 inches from the pilot's eyes. The symbology was depicted in bright green on a black background. The projection area subtended a visual angle of 21° horizontally and 16° vertically.

In the ILS simulation scenario, the aircraft was initially positioned at either side of the localizer course at an intercept angle of about 25°. Each approach had five segments: (i) straight and level at 3500 ft, 180 knots; (ii) constant-airspeed descent at 180 knots to 2000 ft; (iii) straight and level at 2000 ft, gear down and flaps lowered to approach configuration, slow to 150 knots; (iv) level turn to intercept the localizer at 2000 ft, 150 knots; and (v) final descent along the glide path to 1000 ft at 150 knots. Data collection ended when the aircraft passed 1000 ft, but the flight continued until reaching the decision height (370 ft), and then the pilot initiated a go-around. The flight segment lengths were (i) 2.3, (ii) 4.5, (iii & iv combined) 5.5, and (v) 3.2 nautical miles, respectively. Each approach took approximately 7 minutes to complete.

Data Collection

The pilots' eye-movement data were collected with a head-mounted eye camera (RK-726PCI/RK-620PC, ISCAN, Inc., Burlington, MA) and a magnetic head tracker (InsideTRAK, Polhemus, Colchester, VT) at the rate of 60 Hz. Flight variables were recorded at 1 Hz. In addition, the pilots' verbal reports of their current intentions or attitude indicator readings (i.e., "pitch" or "bank") were recorded on videotape.

Each pilot flew 9 data-collection approaches, 3 approaches for each format in balanced order. Before the data collection approaches, each pilot received a briefing and made several practice approaches. After all the approaches were completed, pilots were asked to provide their subjective preference between each pair of symbology formats by marking them on a continuous preference scale (Figure 3).

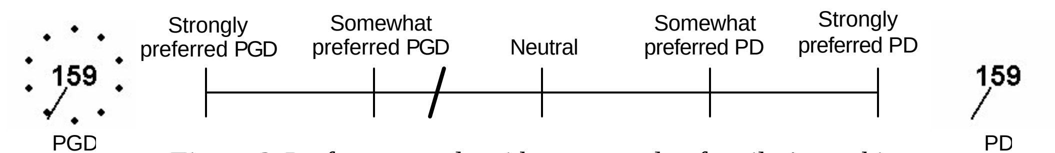


Figure 3. Preference scale with an example of a pilot's marking for the preference between "PGD vs. PD."

RESULTS

Root Mean Square Airspeed and Altitude Errors

Root Mean Square (RMS) airspeed error was computed for segments (i), (ii), (iv), and (v) from the assigned airspeeds, 180, 180, 150, and 150 knots, respectively. A generalized linear model (GLM) repeated measures analysis (SYSTAT 10, SPSS, Inc.) was applied, with the main effect variables being Segment, Format, and Trial Block (block 1 included the first three approaches, block 2 the second three, and block 3 the last three). The results showed that the airspeed error was significantly reduced when PGD was used compared to when D was used ($df = 2$, $F = 4.167$, $p = 0.048$). Figure 4 plots the grand means of all pilots for each format. The result is consistent with that of the USAF study, although the difference between PD and D did not reach statistical significance in this study.

RMS altitude deviation was also computed for segments (i), (iii), and (iv) from the assigned altitudes, 3500, 2000, and 2000 ft, respectively. The same GLM repeated measures analysis was performed. Unlike in the USAF study, no significant format effect was found in this study.

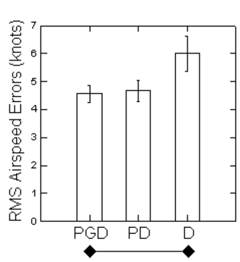
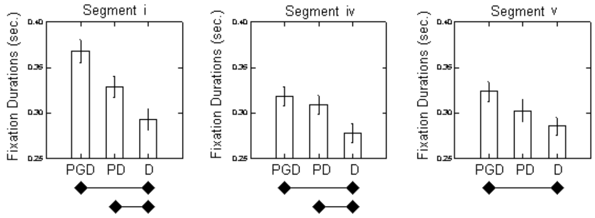
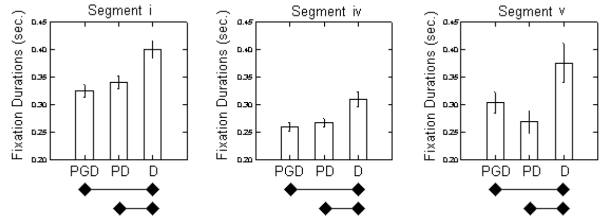


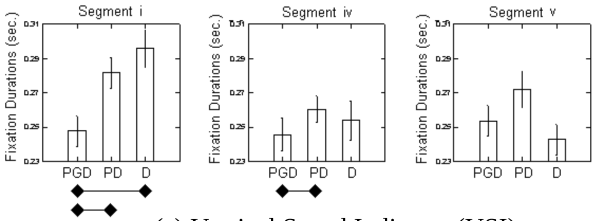
Figure 4. Grand means and standard errors of RMS Airspeed Error. Diamonds connected by a line indicate a significant difference between the two formats ($p < 0.05$) computed by pairwise comparison.



(a) Airspeed Indicator (ASI)



(b) Altimeter



(c) Vertical Speed Indicator (VSI)

Figure 5. Grand means and standard errors of fixation durations (the values before taking logarithms) on (a) ASI, (b) altimeter, and (c) VSI in segments (i), (iv), and (v). Diamonds connected by a line indicate a significant difference between the two formats ($p < 0.05$) computed by pairwise comparison.

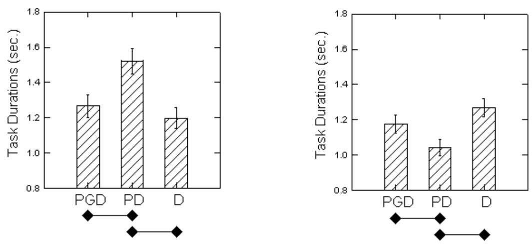
Symbology Fixation Durations and Look Rates

Fixation durations on each HUD symbology were computed from the eye-movement data. Due to positively skewed distributions, the values of durations were transformed by taking natural logarithms. Since each format had a different number of fixations (i.e., "unbalanced" data), mixed regression repeated measures analysis (SYSTAT 10, SPSS, Inc.) was applied instead of a GLM. The main effect variables were Format and Trial Block. Analyses were performed for each flight segment. Figure 5 shows the grand means of fixation durations on the ASI, altimeter, and vertical speed indicator (VSI) and pairwise comparison results in selected flight segments: (i) straight and level, (iv) level turn to intercept the localizer, and (v) final descent. As seen in Figure 5, the fixation durations on the ASI and altimeter showed opposite trends; the durations on the ASI tended to be longer when PGD or PD was used than when D was used, while those on the altimeter tended to be shorter when PGD or PD was used than when D was used. No difference between the two rotating-pointer formats (PDG and PD) was found in the ASI and altimeter fixations. However, a difference between them appeared in the fixations on VSI; the durations on the VSI tended to be longer when PD was used than when PGD or D was used.

The GLM repeated measures analysis with the main effect variables being Segment, Format, and Trial Block also revealed significantly higher VSI look rates (i.e., the frequency of visits per second) when PD or D was used than when PGD was used ($df = 2$, $F = 5.867$, $p = 0.021$).

Flight Task Durations (HMM Analysis)

During instrument flight, pilots usually have several "sets" of instruments to crosscheck together—vertical-tracking instruments (pitch, altimeter, VSI, and glide slope), horizontal-tracking instruments (bank, heading, and localizer), and airspeed-tracking instruments (pitch, ASI, and thrust). A Hidden Markov Model (HMM) based analysis tool has been proposed by Hayashi, Oman, & Zuschlag (2003) to compute the pattern in pilots' scanning, or the sequence of pilots' attention switching among these tracking tasks, from pilots' eye-movement data.



(a) Vertical-Tracking Task (b) Airspeed-Tracking Task

Figure 6. Grand means and standard errors of (a) vertical-tracking task durations and (b) airspeed- tracking task durations. Diamonds connected by a line indicate a significant difference between the two formats ($p < 0.05$) computed by pairwise comparison.

HMM analysis was applied to the eye-movement data from flight segment (iv). The pilots' verbal reports in segment (iv) were used to train the HMM. Analysis showed that the durations on the vertical-tracking task were significantly longer and those on the airspeed-tracking task were significantly shorter when PD was used than when PGD or D (Figure 6).

Pilots' Preference Rankings

The positions of the pilots' markings on the preference scales (Figure 3) were converted to preference scores by measuring the distance from the opposite side of the scale. The scores of the same format were added within each pilot and ranks were assigned (3 for the most preferred, 2 for the second most, and 1 for the least preferred). The rank sum of all pilots indicated that the most preferred format was PGD (rank sum = 16), the second most preferred was PD (12), and the least preferred was D (8) (Friedman test statistic = 5.33, $df = 2$, $p = 0.070$).

DISCUSSION

When PGD or PD was used, the fixation durations on the ASI increased and the RMS airspeed error decreased, compared to when D was used. The increased fixation durations indicate that reading the rotating-pointer movements took extra fixation time, but the pilots could effectively utilize the information to reduce airspeed error.

The fixation durations on the altimeter, on the other hand, decreased when PGD or PD was used, compared to when D was used. In some segments, the fixation duration means of PGD and PD were even shorter than that of the ASI in D format. However, one should be aware that the altitude tends to move faster than the airspeed, and, thus, even a relatively short fixation may have been sufficient to observe the rotating pointer motions. In addition, most flight segments in this experiment were defined by the altitude rather than the airspeed, such as "straight and level." Thus, the pilot may have perceived the altitude as more important than the airspeed. Therefore, it was possible that the pilots took more fixation time to read the altitude and its movement than the airspeed when D was presented.

An interesting difference between PGD and PD appeared in the VSI fixations, and this may help in understanding the value of the gradation marks. When PD was used, the VSI look rates increased and the fixation durations also increased. This may imply that the pilots did not utilize much altitude rate information with PD despite the presence of the rotating pointers. HMM analysis also showed that the pilots spent more time on the vertical-tracking task when PD was used, possibly as the result of the increased fixation demands on VSI, and that extra time was taken away from the airspeed-tracking task. Although the RMS airspeed and altimeter error levels stayed about the same between PGD and PD, this strategy change may have caused the pilots' slight preference for PGD over PD.

CONCLUSION

The rotating pointers (PGD and PD) resulted in smaller airspeed error and higher pilot preference ratings. These results were consistent with the USAF study. Unlike their study, this study did not find any significant format effect in the altitude error.

In addition, the eye-movement data analysis provided further insights into the effects of the rotating pointers and gradation marks. For both the ASI and the altimeter, significant changes in the fixation durations were observed between the rotating-pointer formats (PGD and PD) and digits-only format (D). The results, combined with the RMS airspeed and altitude error findings, confirmed that the rotating pointer formats provide superior scanning efficiency over the digits-only format. The differences between PGD and PD were found in the VSI fixation patterns and the vertical- and airspeed-tracking task durations estimated by the HMM analysis. The increased attentional demand for the vertical-tracking task when PD was used may explain why the pilots slightly preferred PGD over PD. The results provide empirical support for the common belief in the potential advantages of gradation marks.

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