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Improving Bank Angle Representation of the Attitude Indicator Using Monocular Visual Depth Cues

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Abstract

Previous studies have indicated that the attitude director indicator (ADI) used in commercial aviation is suboptimal in representing the bank angle direction, which can lead to confusion, roll reversal errors and increased workload. Confusion about the bank angle direction has been implied in several cases of loss of control in-flight (LOC-I). In the current study, we therefore tested whether bank angle representation can be improved by adding non-disruptive visual depth cues to the ADI. An enhanced ADI was created, in which three monocular cues were added: atmospheric haze (i.e. a gradient in color towards the horizon), a shadow line under the aircraft symbol, and perspective lines on the ground. Airline pilots (n = 25) were tasked with rolling back to level 96 times from unforeseen (30 or -30 degrees) bank angles after experiencing either matching or mismatching (disorienting) roll motion cues in a motion-base simulator. There was no outside visibility and pilots responded using the ADI only. Roll reversal errors and reaction times were compared within-subject between the enhanced and baseline ADI, which were both based on the B747. Pilots were tasked to respond immediately upon presentation of the display, so that their initial interpretation of bank angle direction could be measured.

There was no significant difference in roll reversal errors, and a significant increase in reaction times, when using the enhanced ADI compared to the baseline ADI. This suggests that pilots had slightly more difficulty with reading the bank angle with the enhanced ADI. Of the pilots, 56% preferred the enhanced ADI over the baseline display as it is, 8% had no preference and 36% preferred the baseline ADI. The most valued addition was the perspective lines on the ground, which pilots remarked would also be helpful in recovering extreme attitudes. The most-heard concerns were about potential clutter caused by the added cues, and difficulty with accurate reading of the pitch angle due to the shadow lines. In conclusion, according to the pilots' feedback, the addition of depth cues to the ADI appears promising, but it should be tested using more challenging tasks. Further design changes also appear needed to prevent clutter and facilitate quick reading of the aircraft attitude.

Keywords: Design; Display; Gestalt; Visual perception; Spatial disorientation

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1. Introduction

One of the main causes of loss of control in-flight is spatial disorientation (SD; Belcastro et al., 2017; Newman & Rupert, 2020), which is an erroneous sense of the aircraft attitude and motion relative to the earth. SD can lead to an incorrect interpretation of the attitude indicator (ADI), the primary source for self-orientation when the natural horizon is absent. Misinterpretation of the ADI can cause pilots to respond incorrectly when trying to level the wings of the aircraft. This is known as a roll reversal error (RRE).

Confusion about the bank angle leading to RREs was implied in several recent accidents, such as Kenya Airways Flight KQA507 and Flash Airlines flight 507. It has been argued that the moving horizon (MH) ADI is ambiguous and can cause misinterpretation (Johnson & Roscoe, 1972; Müller, Sadovitch & Manzey, 2018). The MH ADI adheres to the “principle of pictorial realism” (Roscoe, 1968). It is designed to mimic the outside view: the horizon line moves and the aircraft symbol remains fixed. In experiments that were intended to evaluate the AI when the previous bank angle was unknown and without the use of motion, pilots showed a rates of 6.9-8.7% (Müller, Sadovitch & Manzey, 2018; Van den Hoed et al., 2022) and up to 19.4% when they experienced disorienting roll cues (Van den Hoed et al., 2022). These findings indicate that there is indeed ambiguity in the ADI, even for pilots.

One possible cause for this ambiguity is a poor indication of figure-ground relationship in the display. Figure-ground organization, which is part of the Gestalt principles, is the process of how the human brain quickly distinguishes between the foreground (figure) and background (ground) of an image (Wagemans, 2018). The horizon symbol does not optimally satisfy the characteristics of a background, due to it being the moving part and the display lacking depth, which makes it harder to perceive the horizon as something behind the aircraft symbol. Because of this, the pilot may attempt to move the horizon symbol instead of the fixed aircraft symbol. This error is known as horizon-control reversal (Roscoe, 1968).

Solving the display-control motion compatibility and the moving element issues would require changing the dynamics of the display which could induce errors due to pilots having to be retrained. In a previous study (Arrundell et al., 2023) the option was explored of using a dual-layer display ADI: the aircraft symbol and attached symbology was placed in front and the horizon behind with around 2 cm of depth in between. No significant effects were found on roll reversal errors and the stereoscopic effect induced an undesired motion parallax when pilots moved their heads. In the current study we therefore attempted to improve the figure-ground relationship of the MH ADI using visual monocular depth cues. If successful, this could reduce the occurrence of RREs and as a result decrease the number of accidents caused by LOC-I. Pilot error rates and reaction times in rolling back to level were compared between a standard ADI (Figure 1, left) and an enhanced ADI (Figure 1, right), which featured the following visual depth cues: 1) Linear perspective lines on the ground that coincide in the center of the horizon. This is based on the principle that the distance between parallel lines decreases the farther the lines are. 2) Colour gradient in both the “sky” and “ground”, which get less saturated closer to the horizon line, based on the principle of aerial perspective. 3) Shadow line below the aircraft symbol, which gives the illusion that the aircraft symbol is higher than the background.

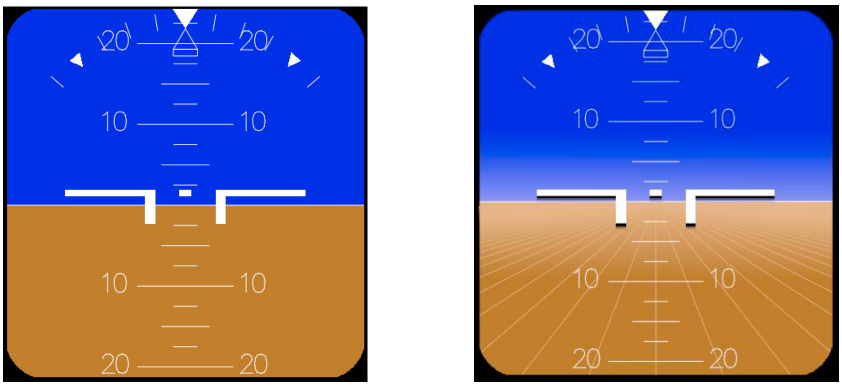

Fig 1. Baseline ADI (left), enhanced ADI (right).

2. Method

2.1. Participants

A total of 25 (22 male, 3 female) commercial airline pilots participated in the study with an average age of 48.9 years (SD = 9.6), and an average total number of 12,436 flight hours (SD = 5,157). All were familiar with flying medium to large-sized aircraft and were in possession of an Airline Transport Pilot License (ATPL). The experiment was approved by the Human Research Ethics Committee of Delft University of Technology (approval #3346) and informed consent was obtained from each participant.

2.2. Apparatus

The experiment was performed in the SIMONA Research Simulator (Fig. 2) at the faculty of Aerospace Engineering of Delft University of Technology. SIMONA features a six-degree-of-freedom full-motion simulator with a hydraulic hexapod motion system. The participant was seated in the left-hand seat of the cockpit (Fig. 1) in front of a collimated 180° horizontal by 40° vertical field of view screen. The outside visuals used in some stages of the experiment were rendered by FlightGear software and projected using three DLP projectors. Audio simulation featured a constant engine and wind noise and the autopilot disconnect alert. Pilots wore noise-canceling headphones to prevent them from hearing the simulator's motion system, however, they could hear the autopilot disconnect alert. A 9-inch tablet was used for a secondary distraction task. The aircraft flight dynamics were simulated using a DLR A320 model. Participants could only control the roll axis, using a control column with electric control loading. The control column contains a control loading model with a spring gradient of 12.0 Nm/rad, a breakout torque of 2.0Nm, and a static and dynamic friction of 0.3Nm. Throttle was controlled by the autopilot throughout the entire experiment. The only instrument provided was a simplified digital Primary Flight Display (PFD), showing the aircraft's attitude, speed, and altitude. A modified autopilot was used to bank the internal aircraft model to the required test conditions. No autopilot actions were fed back to the control inceptors. In this phase, the motion system was either kept still or used to provide disorientation cues to the participant, as described in subsection IV-C.

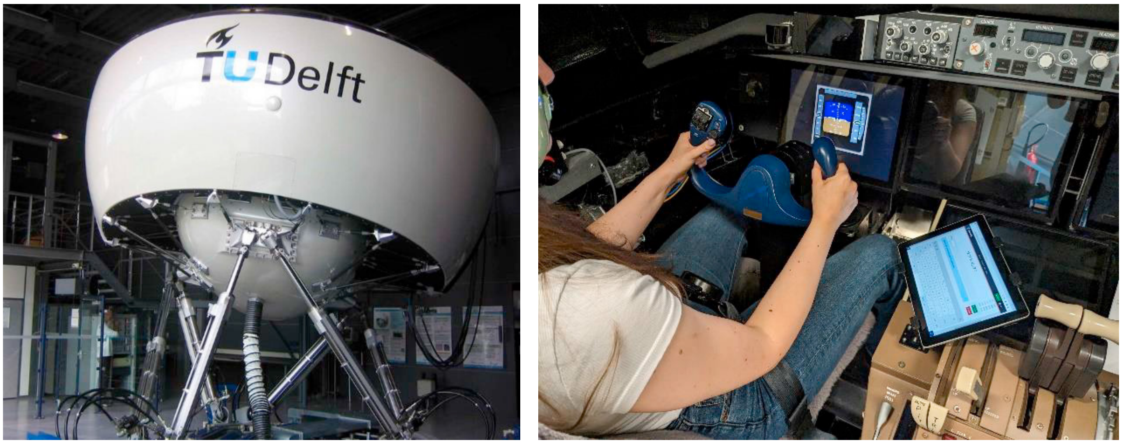

Fig. 2. The SIMONA Research Simulator (left) and the experimental setup (right).

2.3. Experiment procedure

Participants were instructed that they had to roll the aircraft back to wings-level using the ADI, but they were not told that confusing motion cues were going to be provided. They were instructed to respond immediately when the ADI appeared to obtain their intuitive response. Participants familiarized themselves with the simulator and controls by flying for two minutes. For both parts of the experiment, the airspeed remained fixed at 230 knots and the altitude at

10,000 feet. Continuous light turbulence (using a Dryden model of turbulence with σ = 1.0, L = 2,000 m, V = 200 m/s) was added to mask motion onsets. The experimental tasks were divided into two sections, defined by the use of different motion cues to instill confusion regarding the bank angle direction.

In the first section, the same protocol was applied as in Landman et al. (2021) and Van den Hoed et al. (2022). While flying straight and level on autopilot, the simulator was in 60s prepositioned to a bank angle of 3.5°, after which outside visibility reduced to zero and the ADI was covered. The pilot performed a distraction task on a tablet during this prepositioning. Then, the autopilot disconnect alert sounded, the pilot took the control column, the simulator banked back to level, and the ADI was shown. It showed a bank angle of 30 degrees, matching the direction of the roll cue in some runs and mismatching it in other runs. The pilot was tasked with rolling back to level. Two matching runs were performed as practice, and then two matching runs and one mismatching run in randomized order for the baseline ADI, and the same set of three runs for the enhanced ADI. Due to some issues with presentation of the stimuli causing loss of data, and no significant results of this task, this experimental task is excluded from the results in this paper. The results are reported in Van Droogenbroeck (2024).

The second section of the experimental tasks consisted of 96 shorter runs in which the outside visibility was always zero. As illustrated in Fig. 3, each of these runs started without a shown ADI. Participants kept their hands on the control column the entire time. After a four-second pause the cabin tilted to an 3.5° roll angle with a peak rate of 0.04 rad/s and a peak acceleration of 0.075 rad/s^2. The ADI was shown one second later and the participant rolled to level. The ADI could show a bank angle of 30° that was in the opposite direction of the preceding roll cue (mismatching runs), or which matched the direction of the preceding roll cue (matching runs).

Participants performed three matching runs with each display first as practice, and then performed 48 runs in blocks of six with short breaks in between blocks. Run type was divided over matching and mismatching at a 50% ratio, and the order was randomized. ADI type was alternated between blocks, with the starting ADI type being counterbalanced between participants.

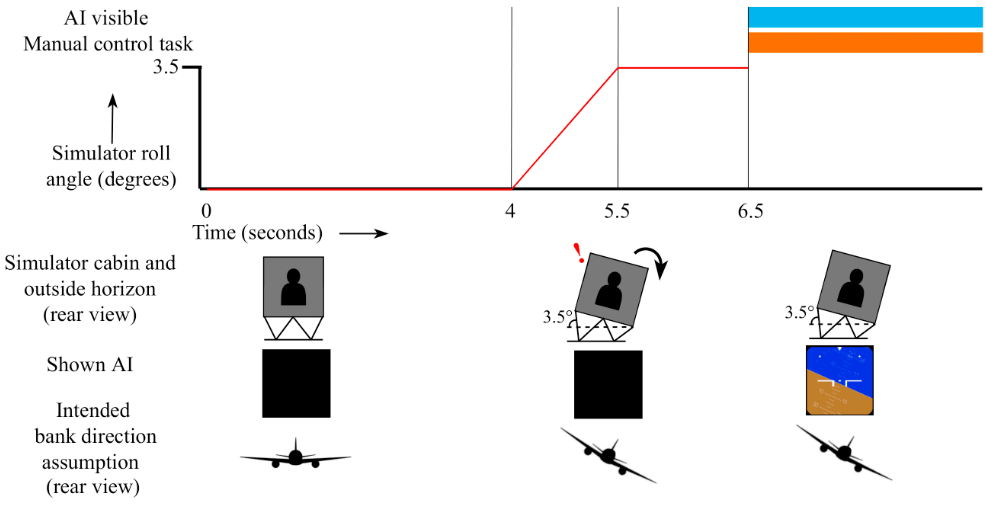

Fig. 3. A timeline of the stimuli in one run. The example is of a mismatching run.

2.4. Dependent measures

The following dependent measures were obtained:

Reaction Time - This was the time between the display presentation and the start of the first control input. The control loading model stays at zero until a torque is exerted above the breakout. The derivative of the control loading model's position was taken and the first instance of it being larger than zero, was seen as the first reaction.

Error Rate - An error was defined as a roll input away from wings-level flight following the AI presentation that caused the control column to exceed 1° of roll deflection, consistent with previous research (Van den Hoed et al., 2022).

Pilot comments - After the experiment was completed, participants filled in a questionnaire consisting of close- and open-ended questions related to their perceived effectiveness of both the displays and experiment procedures. Pilots indicated which ADI they preferred, if the enhanced ADI provide a sense of depth, which ADI made it easier to read the bank angle, and whether they saw issues in using the enhanced ADI. They also pointed out which of the modifications in the enhanced ADI they found most helpful.

2.5. Data analysis

The simulator data of two participants were corrupted and could thus not be processed and analyzed. However, they did perform the experimental tasks so their answers to the post-experiment questionnaire were still included. Statistical analysis was performed using IBM SPSS software. The data were checked for normality. For data that were normally distributed a paired-samples t-test was used to compare the sample means between ADIs (baseline, enhanced). For data that were not normally distributed the Wilcoxon signed-rank test was used to compare the sample medians. As a secondary (manipulation) check, results were also compared between run types (matching, mismatching). Effect sizes (Cohen's *d*) of 0.2, 0.5 and 0.8 will be discussed as small, medium and large, respectively.

3. Results

Fig. 4 shows an overview of the results.

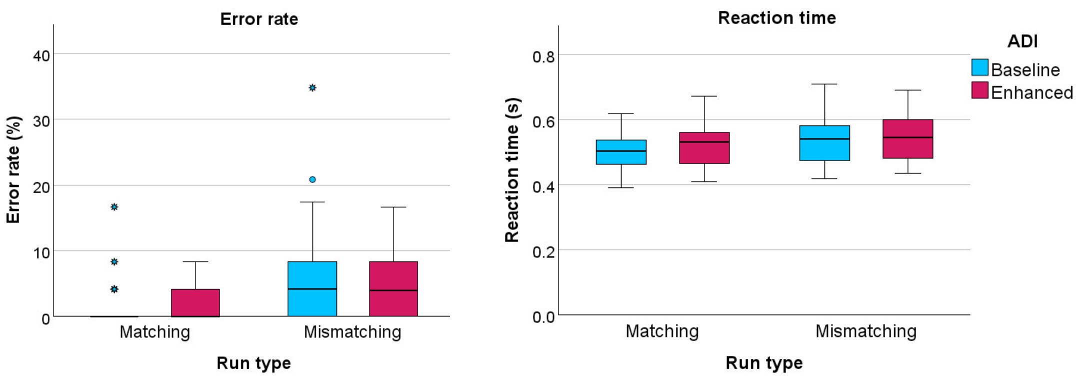

Fig. 4. Tukey boxplots of the error rates (left) and reaction times (right). ° > 2 IQR, * > 3 IQR.

3.1. Error rate

There was no significant difference in error rate between the enhanced ADI, median = 2.0%, IQR = 8.0%, and baseline ADI, median = 2.1%, IQR = 6.0%, $Z(22) = -0.901$, $p = 0.367$. The mismatching runs, median = 4.2%, IQR = 6.0%, induced significantly more errors than the matching runs, median = 0.0%, IQR = 2.0%, Z(22) = -2.983, $p = 0.003$. The first presentation of a motion-opposite run was quite successful, as an error was detected for 52.2% of the pilots. Most of the errors (53.3%) in the mismatching runs were made at the start of the experiment, i.e. during the first 10 encounters of this run type. Of these errors with regard to the first 10 encounters, 68.7% were made with the baseline display and 31.3% were made with the enhanced display.

3.2. Reaction time

Fig. 2 shows the data distribution of the reaction times for both displays in the matching and mismatching conditions. The reaction time was significantly higher for the enhanced ADI, $M = 1.07$ s, $SD = 0.147$, than for the baseline ADI, $M = 1.04$ s, $SD = 0.143$, $\Delta = 0.027$ s, $t(22) = 5.17$, $p < 0.001$. The effect size, $d = 1.08$, was large. The reaction time was also significantly higher for the mismatching runs, $M = 1.09$ s, $SD = 0.151$, than for the matching runs, $M = 1.03$ s, $SD = 0.142$ s, $\Delta = 0.061$ s, $t(22) = 6.28$, $p < 0.001$. The effect size, $d = 1.32$, was large.

3.3. Pilot comments.

Of the 25 interviewed pilots, 56% preferred the enhanced ADI, 36% the baseline ADI, and 8% had no preference. The most-often mentioned reason for preferring the enhanced ADI was that it felt more intuitive due to it being a more accurate representation of the real world. The main reason for preferring the baseline ADI was that it looked less cluttered. Most pilots (80%) indicated that the enhanced ADI created a sense of depth, whereas 20% indicated it did not.

28% Found it easier to read the bank angle with the enhanced ADI, 64% saw no difference and 8% found it harder. The most-selected helpful elements in the enhanced display were the converging lines (80% selected this), color gradient (40% selected this) and shadow under the aircraft symbol (16% selected this). According to the pilots, the converging lines added extra awareness of the bank angle and could also help in discerning sky from ground in extreme attitudes. While some pilots appreciated the contrast created by the shadow, others mentioned it obscured their view of the horizon and made it harder to align the aircraft with the horizon. Four pilots saw problems with introducing the display in operations, stating that it caused too much clutter and that the shadow induced pitch reading errors.

4. Discussion

No significant differences between the baseline ADI and enhanced ADI were found when looking at the error rate. The results thus do not support the hypothesis that adding monocular depth cues may aide in bank angle representation and prevent roll reversal errors.

The results of reaction time also did not support this hypothesis, as we found a significant difference in the opposite than the expected direction: the enhanced ADI caused a significant increase in reaction time, with a large effect size. Even though more pilots found it easier than harder to read the bank angle with the enhanced ADI, this did not follow from the reaction times. This finding coincides with Arrundell et al. (2023), who found an increase in reaction time for a dual-layer ADI compared to a single-layer ADI. The increased reaction time may be caused by our pilot sample being more familiar with the baseline ADI, but it could also indicate that the enhanced ADI was slightly more cluttered.

One explanation for the absence of differences in error rates could be that the task was not challenging enough. Approximately half of the logged roll reversal errors occurred in the first 10 (of 24) encounters of the mismatching runs, and there were six pilots who made no roll reversal error at all. In these first 10 encounters, there is a slight trend visible towards fewer errors with the enhanced ADI, but no statistical analysis was performed on this observation. Multiple participants mentioned that the 30° bank angle used in the experiment is within their "comfort zone" and evokes little to no surprise or concern, even when preceded by a motion cue in the incorrect direction. More extreme bank angles would most likely show bigger differences in reaction time and would make participants have to interpret the ADI under more pressure, possibly increasing any advantage of one of the ADI's. One participant also noted that they knew when they were going to have to give an input due to the motion upset always happening a couple of seconds before the AI would be presented. Varying the timing between the motion cue and ADI presentation may increase unpredictability and make the task more challenging.

A limitation of the current study is that the combined effectiveness of three different adaptations of the ADI is tested at once. This was done because it was assumed that small positive effects of each adaptation would stack to induce an effect that is more detectable. However, it could also be that the effect of one of the adaptations counteracts the effect of another.

Based on the results, it could be useful to test the effect of monocular depth cues in the ADI on roll reversal errors with more challenging experimental tasks which induce more surprise and stress. Based on the pilot's feedback, the shadow under the aircraft symbol should be omitted and the perspective lines on the ground could possibly be reduced in contrast and made a similar colour as the background to reduce potential clutter.

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