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Enhancing Spatial Orientation in Novice Pilots: Comparing Different Attitude Indicators Using Synthetic Vision Systems

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Spatial disorientation (SD) is a common factor in aviation accidents, especially in novice pilots. An experiment was carried out to determine which of four different attitude indicator concepts in combination with two different display backgrounds (abstract vs. synthetic landscape) proves to be the most beneficial for novice pilot performance. Inexperienced pilots had to recover from unusual attitudes by using the standard moving-horizon display, a moving-aircraft display, a frequency-separated display, and a “mixed” display, with the latter two representing hybrid concepts with movements of both aircraft symbol and horizon bar. Participants performed the task of recovering from unusual attitudes most efficiently with hybrid display concepts, suggesting that these display concepts prevent figure-ground reversals and associated pilot errors. Outcomes of the study suggest that the implementation of hybrid display concepts as a backup option when unwillingly entering Instrument Flight Conditions could be a solution for preventing SD in novice pilots.

INTRODUCTION

Loss of spatial orientation (SO) during aircraft navigation is a common factor in fatal aviation accidents (Comstock et al., 2003, Gillingham & Previc, 1996). Collins and Dollar (1996) found that 80.2% of aviation accidents associated with spatial disorientation occur in instrument meteorological conditions (IMC), when pilots have to fly under instrument flight rules (IFR), navigating by reference to the attitude indicator (AI) and other instruments only. From these aviation accidents 85% were the “result of collision with the ground, water or structure” (p.7). Especially untrained and novice pilots who do not have a certification for flying in IMC tend to experience difficulties in flying in adverse weather conditions: Nearly half of all weather-related accidents result from pilots attempting to continue visual flight rules (VFR; navigating solely by reference to outside visual cues) flight into IMC. When continuing to fly under VFR in IMC the probability of having a fatal accident increases to 83% (Roscoe, 2004).

While flying under IMC, pilots need to rely on the AI, an instrument which displays visual information about the aircraft’s pitch angle (nose-up or nose-down) and bank angle (tilting of the aircraft to one side). By doing so it provides crucial information about aircraft attitude, so that the pilot does not have to rely on what he sees (or does not see) when looking out of the window. Conventionally, the AI consists of a small symbol depicting an aircraft and a horizon bar, which divides the instrument into two halves. The top half representing the sky is usually blue. The bottom half representing the earth’s surface is usually brown. Additional degree marks on the display representing pitch and bank angle are also common.

There are several possible design options to convey pitch and bank information via the AI and it remains an open question how to depict this information in a most compatible way (e.g. Previc & Ercoline, 1999; Yamaguchi & Proctor, 2010). The standard way of designing an AI is the ‘inside-out’ or ‘moving-horizon’ display. It represents roll and pitch movements by its consequences in terms of what one would see if looking at the outside world through a porthole in front of the aircraft. That is, the aircraft symbol remains fixed and the artificial horizon-line in the AI rotates or moves upwards or downwards corresponding to the apparent movements of the real horizon line if looking outside from the cockpit. This display fulfills what has been referred to as the “principle of pictorial realism”, which states that a “display should look like or be a pictorial representation of the information that it represents” (Wickens, 2003, p. 152). However, it does not confirm the competing “principle of moving part” which requests that the movements of the display corresponds to the movement of the aircraft, as well as to the steering movement of the pilot. This latter principle is better reflected by the “outside-in” or “moving-aircraft” display which has been used in Russian aircraft for a long time. The moving-aircraft display only depicts pitch movements by means of upward and downward movements of the artificial horizon-bar and roll movements by means of movements of the aircraft symbol. A schematic depiction of both display formats is provided in figure 1.

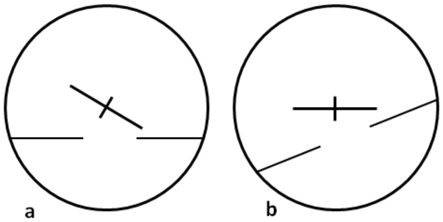

Figure 1: Schematic representation of moving aircraft display (a) and moving horizon display (b) in an ascending right turn.

A number of empirical studies have investigated the compatibility and human performance consequences of these two different AI designs. Whereas no differences were found with respect to attitude tracking, i.e. situations where pilots are constantly checking the display and making control inputs to correct small deviations in order to maintain a given attitude (Yamaguchi & Proctor, 2010), the moving-aircraft display was usually found to be significantly better (more suitable) when pilots had to recover from suddenly occurring unusual attitudes (Johnson & Roscoe, 1972; Lee & Myung, 2013;

Roscoe, 1968). Specifically, novice pilots, not yet trained for instrument flying, committed much more reversal errors in their initial correction movements and/or needed longer time to recover when flying with a moving-horizon display compared to a moving-aircraft display. Seemingly these pilots intuitively misinterpreted the movements on the display as representing aircraft movements. This suggests a dominance of the principle of moving part over the principle of pictorial realism and has led researchers to call the usability of horizon-moving displays into question (e.g. Previc & Ercoline, 1999). One possible explanation for the disadvantages of moving-horizon displays, that has already been put forward during the early years of flying, involves a figure-ground reversal effect: Within the context of extreme flight attitudes and a moving-horizon AI, the pilot no longer sees his aircraft as the mobile part in the world but his display as the mobile part which moves against the stable cockpit panel background (Grether, 1947). This could lead to a figure-ground reversal in the pilot's mental model, ultimately letting him to believe the part he has influence over via control inputs is the horizon bar instead of the aircraft symbol. It instantly seems plausible that such an effect might be responsible for the research results reviewed above taking into account that most, if not all, of the research was based on early generation of moving-horizon displays which typically represented single round instruments of comparatively small size. However, in current generations of glass-cockpits the size of displays has significantly increased which now provides new possibilities of integrating more realistic images of the real world in the AI by means of synthetic vision system (SVS) technology. It seems obvious that the use of SVS might strengthen the "pictorial realism" of a moving-horizon AI, thus making the figure-ground relationship in the display less ambiguous. Accordingly it might be assumed that SVS technology might diminish or even reverse the disadvantages of moving-horizon displays compared to moving-aircraft displays. Moreover, the design of hybrid displays might be possible. These displays combine motion relationships from both the moving-horizon and the moving-airplane display, having both parts in the AI move in certain relationships to each other, thereby making control reversals less probable. One such concept has already been proposed by Roscoe and colleagues (frequency-separated display; Roscoe & Williges, 1975; Roscoe, Corl & Jensen, 1981).

The scope of this paper is to revisit the compatibility issue of AI display design in the context of SVS technology. For this purpose, student participants without prior flying experiences were required to perform attitude recoveries with four different AI designs, i.e. moving-horizon, moving-aircraft, and two hybrid designs, and either of two backgrounds, i.e. abstract vs. synthetic landscape.

METHOD

Participants

All participants were TU Berlin staff or students recruited through opportunistic sampling. A total of 30 participants, of which 14 were male and 16 were female, took part in the study. The average age of participants was 25.96 years (*SD* = 3.2). None of them had any prior knowledge of flying, whether in a simulator, nor in real life. Participation was compensated with a payment of 5 Euro (about 6.80 US$) per person. An experimental session took around one hour.

Apparatus and Tasks

The research simulator was situated in a laboratory of the Technical University of Berlin. Four computers were connected over a local area network to generate the primary flight display (PFD) including the AI instrument, a navigational map and the view out of the window. The fourth computer was needed to start and stop flight scenarios via the software UltraVNC version 1. The research simulator consisted of a fixed base mock-up replication of a Cessna 172 Skyhawk SP G1000 Cockpit which was placed on top of a desk. The open source flight simulator FlightGear was used as the simulation model. A Saitek Pro Flight Yoke System USB steering yoke was screwed onto the desk in front of the left monitor on which the PFD was simulated. The right monitor showed a navigation map of the terrain, pilots were flying above. The view out of the window was projected onto the wall above the cockpit mock-up. 16 unusual attitude recoveries were flown with every AI, which had to be performed as quickly as possible. These included recoveries of four different bank angles (30, 60, 90 or 120 degrees) simulating a surprising change of aircraft attitude, which were presented four times each. Each bank angle was presented as a tilt to the left or right and with pitch either 15° up or 15° down. Each attitude change was presented in an unpredictable way after some time of stable horizontal flight.

Design

The study was conducted as a 4(type of display) x 4(bank angle) x 2(display background) mixed design. The first factor was defined as within-subjects factor and involved four levels: Participants flew with a moving-horizon display, a moving-aircraft display, a frequency-separated display, and a "mixed" display. The frequency-separated display differs from the abovementioned displays to that extent that it does not only depict pitch and bank information but aileron information as well. Every aileron input executed is reflected in a corresponding movement of the aircraft symbol in the same direction as the steering wheel. Pitch and bank attitudes are indicated conventionally in the same ways as in a moving horizon-display. In the mixed display, both the airplane and the horizon symbol move in a certain ratio to each other, thereby depicting roll and pitch angles. The angle between aircraft and horizon line does depict the actual bank angle of the aircraft. The different types of displays are presented in figure 2. The second factor was also defined as a within-subjects factor and included the different degrees to which the aircraft banked. The aircraft could either bank to a degree of 30°, 60°, 90° or 120°. The third factor involved the two different *display backgrounds* and was operationalized as a between-subjects variable. One half of the participants flew with a SVS background whilst the other half of the participants flew with a classical blue-sky brown earth background (see figure 3). In summary, every participant flew 16 recovery tasks with every AI and only one display background, i.e. performed a total of 64 single tasks.

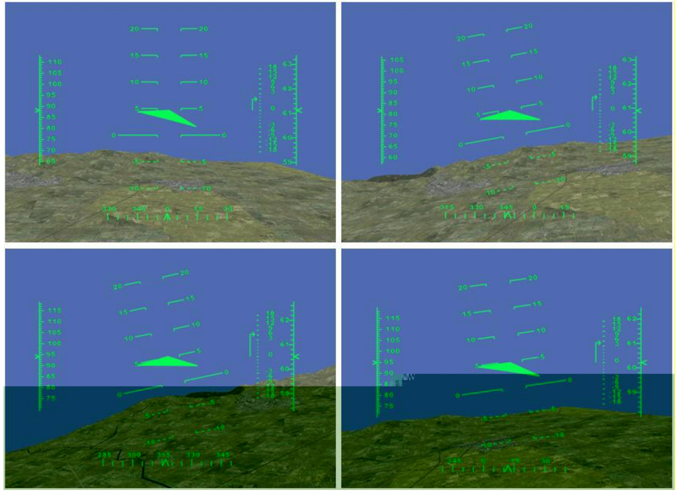

Figure 2: AIs (with SVS backgrounds) depicting a climbing turn to the right, from upper left in clockwise direction: moving-aircraft display, moving-horizon display, mixed display, and frequency-separated display.

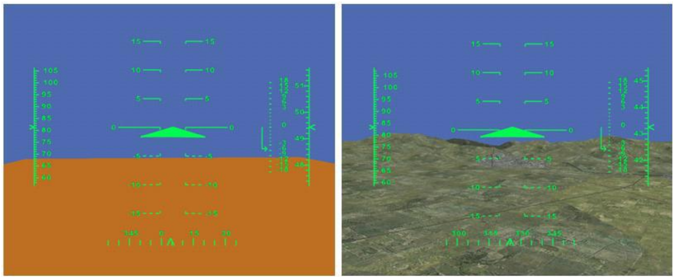

Figure 3: Classical (left) and SVS display background (right).

Performance measures

Performance measures were derived from log-files, which contained the complete steering input of each participant. There were three dependent variables. The first dependent variable was *time to initial control input*. This was defined as the time from the unusual attitude presentation to the first control input that was recorded. This dependent measure is important because it represents the time it takes to recognize and process the aircraft attitude portrayed via the different attitude indicators and backgrounds.

The second dependent variable was the *total recovery time*, which was defined as the time it takes to bring the aircraft in a stable position minus the time to initial control input. Due to the fact that in this study all pilots were novices and had no experience in flying an airplane or holding it in a stable position whatsoever, a stable position was defined as holding the aircraft between a pitch of ±5° and a bank of ±5°. The aircraft had to be held between these ranges for at least 2.5 seconds in order to be rated as a success. This dependent variable is important because it shows how an instrument supports pilots in the process of bringing an aircraft back to a stable straight and level flight after being confronted with an unusual attitude.

The third dependent variable was the rate of reversal errors. Errors were defined as a control input that caused the aircraft to turn even further to the side it was already banked to. Shortly speaking, if an aircraft was tilted to the right, the correct control input would have been to steer the yoke to the left and vice versa. If pilots committed an error while recovering from unusual attitudes, this would have meant that information conveyed by an AI was not easy to interpret or even ambiguous.

Procedure

There was an accommodation phase as well as a practice session before the data collection sessions started. Accommodation phase started with one minute of free flight during which participants could become acquainted with the simulator without further instructions from the researcher. To guarantee a similar level of understanding of movement relationships between the yoke and the aircraft, as well as of proficiency in steering the aircraft, a standardized text was read to the participants to describe several flight tasks that were to be flown. During the experiment, participants had to recover from unusual attitudes, which were introduced randomly. They had to master this task using four different AIs. Attitude changed every 20 seconds, leaving exactly this amount of time to the participant to recover to straight and level flight. Flight level was automatically reset to 6000ft for each attitude change to prevent participants from losing too much altitude during the course of the 16 attitude recoveries per AI.

Hypotheses

In accordance with earlier findings it was assumed that the moving-aircraft AI in combination with the classical blue-sky-brown-earth background would be beneficial in terms of fewer initial steering errors and shorter reaction times (RT) compared to the moving-horizon display. Accordingly, it was theorized that participants would commit more errors and have longer RTs with the moving-horizon AI. Furthermore, it was assumed that these differences in performance measures would disappear or even reverse when each of the two attitude indicators are combined with the SVS background. A computer generated terrain on the PFD should enable the novice pilots to maintain a stable mental model of the flight situation, thereby having shorter reaction times and committing less control reversal errors, bringing performance measures for the two displays more in line with each other.

It was further theorized that overall performance with both the frequency-separated display as well as with the mixed display in terms of errors and RTs would be better than with the two classical display types, independent of the display background. This was assumed because both types of hybrid displays fulfill both relevant compatibility principles, i.e. the ‘principle of the moving part’ and the ‘principle of pictorial realism’.

RESULTS

Time to initial control input. Overall, participants needed 0.9 seconds to give an initial control input with the SVS display background (SD=0.29) and 0.78 seconds to give an input with the classical background (SD=0.26). With each display being separately, it took participants 0.93 seconds to initiate a control input with the moving-aircraft display. With the moving-horizon display, the frequency-separated display and the mixed display it took 0.82, 0.84 and 0.76 seconds respectively. The 4(display type) x 4(bank angle) x 2(display background) analysis of variance (ANOVA) did not confirm that the participants' reaction to unknown attitude presentation was faster with the classical background than with the SVS background (F(1,28)=2.53, p=.122). However, it revealed a significant main effect of *display type* (F(1.7, 47.8)=4.85, p=.016). Post-hoc Bonferroni paired comparisons of display type revealed that participants were faster in giving initial control input with the mixed display than with the moving aircraft display (p<.05). Other comparisons did not prove to be significant. In addition, the main effect of *bank angle*, became also significant, (F(2.2, 62.5)=8.16, p=.000). Means and standard errors for this effect are shown in figure 4 (left side). Responses to the more extreme shifts of bank angles (120° and 90°) were faster than responses to sudden shifts of bank angles by 30°. No significant interactions were found

Total recovery time. The 4x4x3 ANOVA of total recovery times yielded significant main effects of *display type*, (F(9,84)=14.64, p=.000) and *bank angle*, (F(3, 84)=37.21, p=.000), as well as a significant *display type* x *bank angle* interaction (F(5.67, 158.7)=23.75, p=.000). Overall, mean total recovery times were shorter for the hybrid displays than the moving-horizon or the moving-aircraft display. A priori planned post-hoc comparisons (Bonferroni) revealed that participants were faster recovering from unusual flight attitudes with the mixed display (4.82 sec) than with the moving aircraft display (5.65sec; p<.05) and the moving horizon display (5.91 sec; p<.05), as well as with frequency separated display (5.19 sec) than with the moving horizon display (p<.05). Means and standard errors for recovering different bank angles with different display types are shown in figure 4 (right). Bonferroni post-hoc paired comparisons of bank angles revealed that participants were overall faster in bringing the aircraft back to straight and level flight from a bank angle of 30° than they were for all other bank angles (all p<.05). The interaction effect was due to the fact that the recovery times with the moving-aircraft display turned out to be the slowest compared to all other display types for bank angles of 30°-90°, yet the quickest for the most extreme bank angle of 120°. No significant main effect of *display background* (F(1,28)=.69, p=.415) nor any interaction involving this factor was found.

Errors. Errors were defined as an initial control input that caused the aircraft to turn even further to the side it was already banked to. Each participant had to react to 64 sudden attitude changes, thus 64 errors could be committed by each participant. In total, 230 errors were committed by all 30 participants. Error rate per display type showed that most errors (78) were committed with the moving aircraft display. With the moving horizon display, the frequency separated display and the mixed display, error rates were 69, 46 and 37, respectively. When further dividing errors, not only per display type but also per display background, it was found that overall fewer errors were committed with the SVS background than with the classical display background. However, the ANOVA did not reveal this main effect of *display background* significant, (F(1,28)=1.93, p=.175).

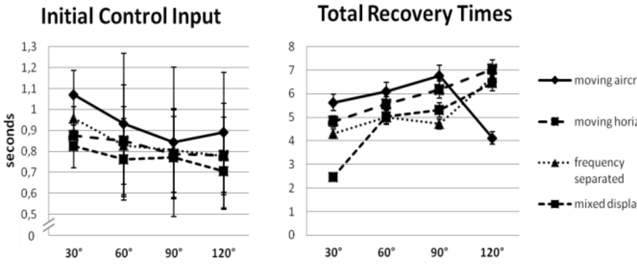

Figure 4: Time to initial control input per display type and bank angle (left). Total recovery times per display type and bank angle (right).

There was a significant main effect for *display type* (F(1,28)=4.86, p=.004). Bonferroni post-hoc paired comparisons of display type revealed that participants committed more errors when recovering from unusual flight attitude with the moving aircraft display than with the frequency separated (p<.05) and the mixed display (p<.05). Furthermore, significantly more errors were committed when using the moving horizon display than when using the mixed display. No significant main effect was found for *bank angle* (F(1,28)=1.01, p=.365). Moreover, a significant two-way interaction between factors *type of display* and *bank angle* was found, (F(5.652, 158.265)=2.857, p=.013). This interaction seemed to have resulted from the fact that participants committed significantly more errors when recovering from a 120° bank angle using the moving aircraft display compared to when using one of the other three displays.

DISCUSSION

The scope of this study was to compare several AI concepts along with two display backgrounds in terms of novice pilot performance. More specifically it was investigated to what extent SVS display backgrounds would reverse earlier findings, which point to a general advantage of a moving-aircraft display, in favour of the standard moving-horizon display. It was also explored to what extent different types of hybrid displays would provide general advantages independent of the display background.

The first hypothesis was not supported by the data. Contrary to our expectation, the moving-horizon display generally led to equal or even better performance than the moving-aircraft display. The only exception was the recovery from extreme bank angles of 120° which were performed quicker with the moving-aircraft display. These results emerged independent of whether the background of the AI was abstract or a synthesized picture of the environment. It contradicts earlier findings, which indicate an advantage of moving-aircraft display designs when using an abstract AI display background (e.g. Gardner & Lacey, 1954; Previc &

Ercoline, 1999). One possible explanation for this discrepancy could lie in the differences between the design of classical AIs, investigated in the earlier studies, and the general design of PFD as used in our research. When looking at the body of research that has been conducted on this topic, it becomes obvious that most of it was carried out between the 1940's and the 1980's. AIs used in earlier studies were small, round instruments that were not integrated with other elements of the cockpit. Due to their smaller size and their clear cut delimitation to the cockpit panel, it seems plausible that these types of instruments were particularly prone to the figure-ground reversal effect described in the introduction, which have been proposed to explain the advantage of moving-aircraft configurations (Grether, 1947). Accordingly, it is probably much more intuitive for pilots to link their steering movement directly to the movements of the display (as in a moving-aircraft design) than a reverse coupling (as in the moving-horizon display). In the current study a much larger PFD design was used which not only differed from the earlier displays with respect to its size but also to the obvious presentation of the artificial horizon as background in relation to the instrument information. All instruments of the PFD were superimposed onto the display backgrounds without having the airspeed indicator, the altimeter and the heading indicator highlighted through a black background as it is done in conventional PFDs. Although most PFDs make use of a black background to highlight parts of the PFD, designs similar to the one used in this experiment are produced and employed for example by Garmin and Cessna. The nonexistent boundaries between display background and instruments could have prevented pilots from having figure-ground reversals with the moving-horizon display: By looking at a large and coherent display, the illusion of looking out of the window is stronger than when looking at a small round AI. Independent of whether land and sky were presented in an abstract or more natural way (SVS) this feature could have been supportive for creating the effect of looking out of the cockpit window, thus decreasing the differences between moving-aircraft and moving-horizon displays. Even more important and interesting than the effects for the moving horizon vs. moving aircraft displays are the effects found in the present study for both types of hybrid displays. Given that the hybrid displays used in the present study confirmed both, the principle of the moving part and the principle of pictorial realism, it was assumed that they should provide advantages for novice pilots independent of the display background. Our results provide at least partial support for this assumption. Analysis of times to initial control input showed that performance with the mixed display was indeed significantly faster than with the moving-aircraft display. Furthermore, total recovery times were significantly faster with the mixed as well as the frequency-separated display than with the moving-horizon display. Similarly, performance with the mixed display was also significantly faster than with the moving-aircraft display. Finally, significantly more errors were made when using the moving-aircraft and the moving-horizon display than when using a hybrid display. Overall, this pattern of results suggests that the naïve participants used in the present study performed best with the mixed display. It is to be noted that this type of display was the most artificial one because it combined display movements of the aircraft symbol as well as the horizon but none of these movements corresponded to the real world. By moving half the angle of the "real" rolling movement of the aircraft or the perceived horizon, only the final angle between the banked aircraft and the horizon corresponded to the true relationships. Obviously, this type of design provided two advantages which made it intuitive and easy to understand for the participants: (1)by combining the two movements relationships into one display, the two design principles were integrated (2) extreme deviations from a horizontal attitude of the aircraft where depicted in only moderate angles on the display, thereby making it comparatively easy to identify the direction of necessary steering actions quickly. Even though such a mixed display might be most confusing for pilots trained in instrument flying, it seems that it might support other pilots best in cases of unforeseen and rare occasions where it is necessary requirements to correctly identify and correct the attitude of their plane, based on instrument information only. Overall, outcomes of this experiment make a re-evaluation of earlier experimental outcomes advisable in the light of progressed technical development in cockpit instrumentation, associated altered AI attributes, as well as new possible design options for AIs.

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