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The effect of the roll index (sky pointer) on roll reversal errors

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Abstract

This study examines the effect of the placement of the roll index (also known as the "sky pointer") in artificial horizons on roll reversal errors. Roll reversal errors (steering the wrong way, i.e. making a bank angle steeper rather than recovering from it) have been known to contribute to loss of control accidents in aviation. We assessed the roll recovery performance of 13 commercial pilots on a total of 390 trials, using an experimental set-up that tested three different sky pointer configurations: one commercial (roll index on top, slaved to the horizon), one General Aviation (roll index on top, slaved to the aircraft), and one military (roll index at bottom, slaved to the horizon). Performance on the commercial artificial horizon was almost five times worse than on the other two. The results point to the primacy of the control-display compatibility principle as mechanism for producing the great performance difference, and raises serious safety concerns with respect to commercial-type artificial horizons now being introduced (via LCD screens) to General Aviation aircraft.

Keywords: Attitude indicator, artificial horizon, pilot performance, bank angle, instrument flying, control-display compatibility

Introduction

The accident that occurred to a SAAB 340 after taking off from Zurich in early 2000 (FOCA, 2001) is suspected to have been caused by loss of control. According to the interim report of the Swiss Federal Office of Civil Aviation (FOCA) the aircraft banked slowly to one direction and then after a hesitation, bank angle increased to an attitude that made recovery impossible. In several international summaries of accident reports, loss of control has been determined to be one of the main causes of several incidents and accidents involving large transport category aircraft (e.g. FSF, 1997). Test pilots who perform maneuvers that require accurate bank angle capture in commercial aircraft, as well as general aviation pilots who transfer onto larger transport aircraft, have also encountered a tendency to initially recover from a steady bank angle in the wrong direction when using the Attitude Display Indicator (ADI) as reference (e.g. Roscoe, 1997). This tendency, known as roll reversal error, has not been as evident in military aircraft that have a different position for their roll (bank) angle index. In military aviation, factors other than ADI referencing often precipitate a loss of control (Gillingham, 1992).

The role played by the "inside-out" configuration (see figure 1), that characterizes most Western ADI's, has been the subject of intense debate and scrutiny in aerospace human factors for decades. The "inside-out" set-up dominates Western aviation cockpits, despite the often demonstrated superiority of an "outside-in" representation, especially with respect to the recovery from a static bank angle (Roscoe, 1968; 1975; Previc & Ercoline, 1999).

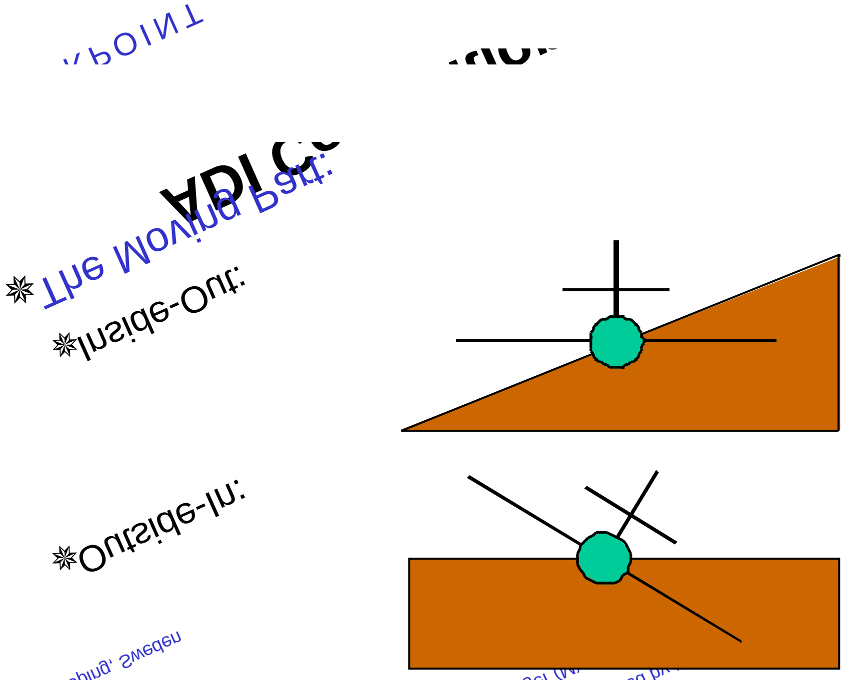

***Figure 1**.: The concepts of Inside-Out vs Outside-In*

Over the decades, multiple hypotheses for better roll recovery performance with an outside-in ADI have been put forward and tested, among them control-display compatibility between control stick movements and the artificial horizon movement on the display (Warrick, 1947; Wickens, 1992); figure-ground relationship (i.e. the relationship between aircraft symbol (figure) and horizon (ground), where inside-out representations would confuse or reverse figure and ground (Fitts & Jones, 1947; Johnson & Roscoe, 1972); field of view (FOV), where the typical 5° FOV "porthole" of an ADI would be inferior to broader views (up to 70°) (Kelley *et al.*, 1961) and neuropsychological mechanisms (Previc, & Ercoline, 1999). The latter hypothesis proposes that "peripersonal" (near space) displays are treated differenty by the brain than the world contained in ambient extrapersonal space (the most valid reference frame for spatial orientation). What links this research is the consistent superiority of an outside-in ADI representation: pilots perform better with it (Gardner, 1954; Roscoe, 1968; FAA, 1996); they themselves prefer it (Browne, 1954); they have been shown to use the outside-in mental concept even when flying with an inside-out ADI, and no amount of overlearning on the inside-out ADI can overcome their preference for an outside-in configuration (Kovalenko, 1991). Since the introduction of Head Up Displays (HUDs), the principle of conformity has made the western ADI convention more intuitive when it overlays the outside world, but even this is not uncontested. For example, recovery from unusual attitudes using inside-out HUDs turns out to be extremely difficult (Previc & Ercoline, 1999).

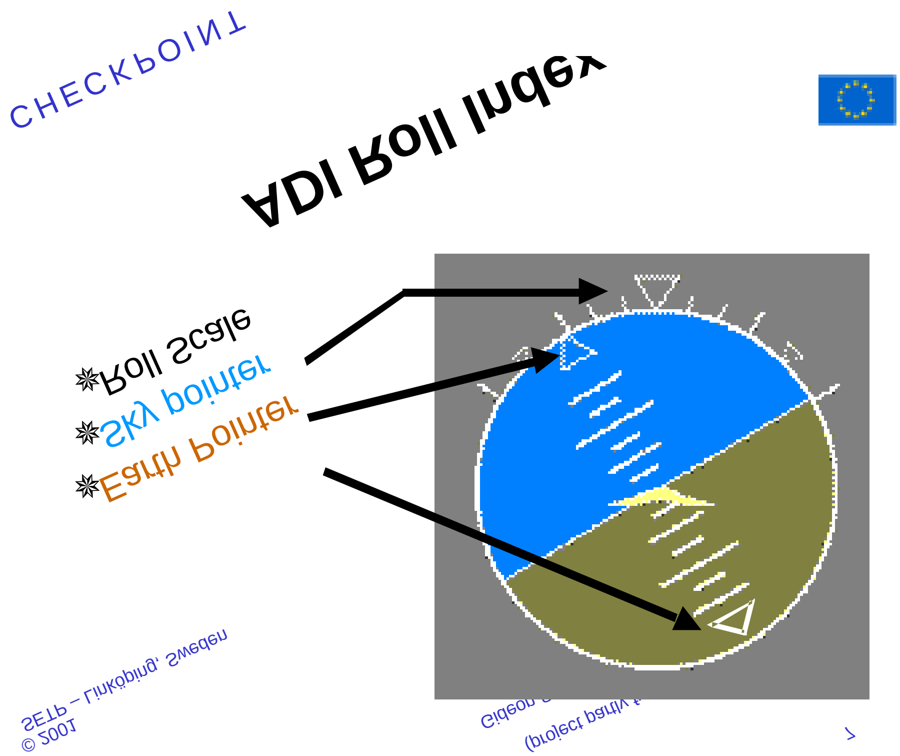

Figure 2. *ADI terms*

The part played by the roll index, or "sky pointer" on the ADI, in contrast, has hardly been explored systematically (see figure 2). The purpose of the study reported in this paper was to extract and highlight the effect of different roll index positions on roll reversal errors. Basic pilot instrument training focuses on the use of the ADI. The pilot is taught to make an open-loop attitude change on the ADI and then check the effect on other flight instruments. In roll, the pilot is taught to use the roll index to achieve and maintain a certain bank angle with the required precision. Three different conventions are being used in Western aviation today (see figure 2):

- Commercial: roll index slaved to the moving horizon;
- Military: roll index slaved to the moving horizon but located on the bottom of the ADI (the "sky pointer" is really an "earth pointer");
- General Aviation (GA): roll index slaved to the aircraft symbol and located on the top of the ADI.

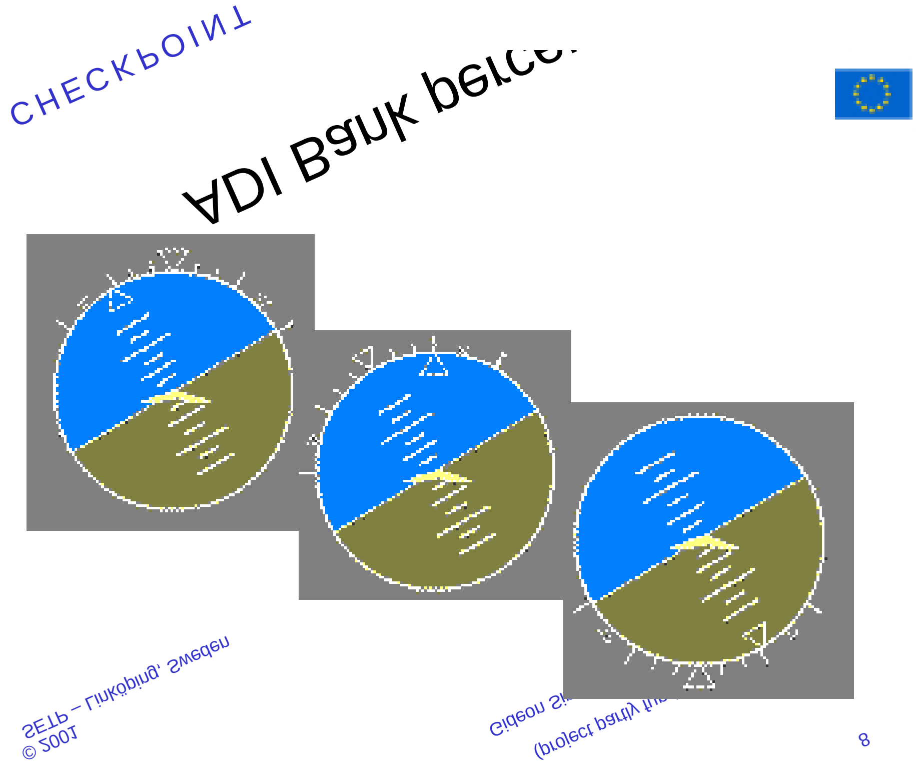

Figure 3*: The three methods of displaying roll index on an ADI*

The parallel existence of these three different placements/movements of the roll index may present safety challenges. First, pilots typically transfer across the different cockpit display formats. Thus, military and GA pilots may one day fly commercial aircraft (where the roll index moves in the opposite direction from what they are used to). In addition, "glass cockpit" (typically LCD) displays are being introduced in more and more general aviation aircraft (cf. FAA, 1987), and their computer-generated ADI's follow the commercial format where the roll index is slaved to the horizon rather than to the aircraft. Thus, similar or identical light aircraft types, flown by the same general aviation pilots, may have roll indexes moving in opposite directions. Given the history of loss of control accidents, this should raise considerable safety concerns.

Figure-ground confusions, porthole limitations and peripersonal processing would have limited influence on the impact a roll index has on bank recovery performance. In the case of the roll index, the figure (sky pointer) and ground (blue ribbon or background) are rather unambiguous; the porthole limitations may not apply since the sky-pointer is not a similar representation of outside reality; and peripersonal processing may not be responsible for the same reason.

The principle of control-display compatibility, however, would be a strong contender in predicting differences in roll recovery performance across the three ADI conventions. Interestingly, in all ADI's there is control-display compatibility in the pitch axis: with a forward movement of the control column or control stick, the aircraft symbol moves down and vice versa. This, however, is not the case in roll. With a skypointer slaved to (and located above) the horizon (a sort of "fly-to" arrangement preferred in commercial and other electronic ADI's), recovery from a bank angle requires the control to be moved in a direction opposite to where the roll index will go. In the military ADI, the compatibility problem is solved by converting the roll index into a "earth pointer". Instead of getting it to point straight up for roll recovery, pilots need to get it to point straight down, and, when slaved to the horizon, control movements could be seen as being compatible with pointer movement (depending on what part of the control pilots mentally refer to: the top or the bottom). Yet most elegant appears to be the general aviation ADI, where roll index and control movement are always in harmony. For example, for recovery from a right bank, the pilot moves the control *and* the roll index to the left. Thus, despite all representations being inside-out, there may be differences in roll recovery performance because of different roll index placements. If the control-display compatibility principle with respect to roll indexes has bearing on pilots' performance in roll recovery, it should be expected that the general aviation representation would score best, followed by the military set-up, followed by the commercial one.

Method

In order to explore these issues, and to gain a deeper understanding of the contribution of the sky pointer in roll reversal errors, experiments were conducted in which the position of the roll index was varied according to the three different conventions, while keeping the inside-out configuration. The bank angle was varied randomly along the normal operational range across trials, but, in order to be sure about the source of performance variance, pitch angles were kept unchanged (at 0°).

13 pilots were selected (aged 38-58 years; mean age 45; experience between 1200 and 14000 flying hours) who all flew commercially (and had done so for at least 5 years) and had backgrounds in both military and general aviation. The purpose of this selection was to guarantee some familiarity with all ADI formats, while drawing from the population currently most exposed to the commercial ADI. Each pilot was given a 10 minute briefing that explained the purpose and nature of the experiment, followed by a 5 minute training session using the commercial ADI (the one presently used by all). Pilots participated voluntarily (unpaid) and were unaware of the aim of the experiment or its hypothesis, and were instructed to recover to a wings level attitude and observe the initial bank.

Using a PC set-up, the three ADI set-ups were presented one after the other, in a representation resembling the newer LCD ADI's, with 10 trials for each set-up. Each pilot thus conducted 30 trials, with the typical experiment lasting about 20 minutes. The order of format presentation was randomized across the pilot sample in order to offset any learning effects. In each trial set, bank angles were varied randomly across an operational range of up to 50° in both directions. ADI's with a static bank angle were presented for 1 second, after which the pilot had 10 seconds to recover from the bank angle using a computer joy stick. The time of presentation (1 second) and static bank angle were used to mimic the kinds of situations that were the interest of this study (FOCA, 2001). The experiment relied on an automatic test sequences and recordings, with no experimenter intrusions. The direction of the initial recovery was recorded, as well as response latency (RT), that is, the time to start the initial recovery. Following the recovery attempt, the pilot was asked to indicate the perceived bank angle within a range of 10°. This secondary task was given in order to ensure that pilots were using the ADI for precision bank angle determination, focusing them on the roll index. Direction of recovery, RT, and pilots' estimates of bank angle were all recorded automatically for later analysis. At the end of each test the subject was asked to his preferred ADI prior to disclosure of the results.

Results

Pilots commented on the set-up and the tasks required of them as being realistic given their purpose, and the allowed observation time as sufficient. No technical anomalies occurred during any of the 390 trials. A total of 385 individual trials could be used for analysis, because 5 trials (three from the military and two from general aviation ADI and by four different pilots; each the first of the set) were unusable due to failure of the pilot to reply. In these cases, pilots appeared to be taken by surprise by the sudden appearance of the first stimulus. Figure 4 displays the average roll reversal error rate and standard error of the mean for all three ADI's.

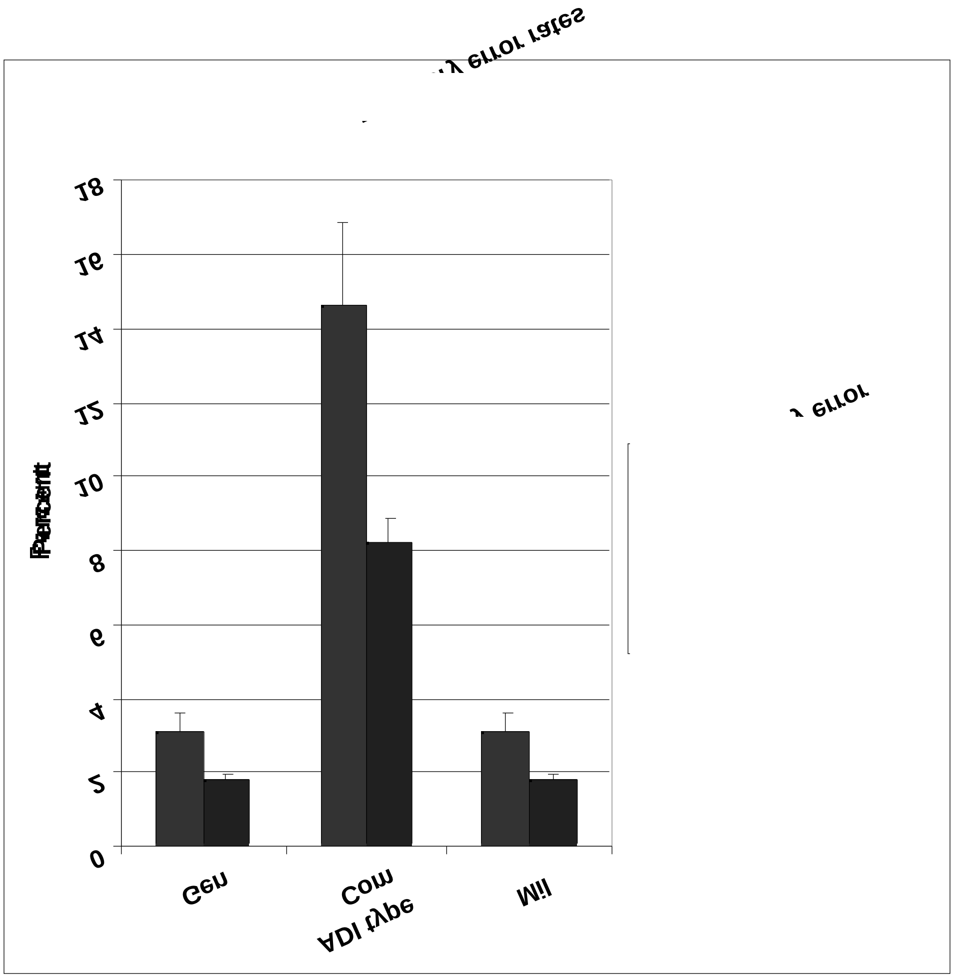

Figure 4*: Errors in roll recovery for the different ADI types*
(shaded areas represent truncated error rates; black areas non-truncated rates)

While recovery on the military and General Aviation ADI was roughly similar, immediately obvious was the inferior performance on the commercial ADI—ironically the ADI currently used by all pilots tested. One pilot even made 100% roll reversal errors with the commercial

ADI, and subsequent probing revealed that any misunderstanding was not the reason for his performance. A Chi-Square test (df = 12) was performed (and not an Analysis of Variance) since the correctness of the direction of recovery was to be compared; not the size of any deviation. It confirmed that performance on the commercial ADI was significantly worse ($P\{X^2 \geq 141,79\} < .01$) than performance on the general aviation ADI ($P\{X^2 \geq 2,67\} > .99$) and the military ADI ($.98 > P\{X^2 \geq 4,83\} > .95$). The data set was truncated by removing both the highest and lowest scores from each ADI, in order to eliminate the extreme score by one of the pilots and to make sure that any outside factors (that would be responsible for extremely poor performance) were kept out of the analysis. The results of the Chi-Square test on the truncated set (df = 10) showed that the commercial ADI still scored worse ($P\{X^2 \geq 47,68\} < .01$), compared to the general aviation ADI ($P\{X^2 \geq 2,28\} > .99$) and the military ADI ($.7 > P\{X^2 \geq 7,47\} > .5$).

An analysis of variance (ANOVA) was conducted on response latency (RT), which revealed that there were no significant differences across the three ADI types ($F(2,24) = .17$, $p < .85$) (mean RT on the general aviation ADI was 630 ms, on the military ADI 623 ms. and on the commercial ADI 610 ms.). In other words, pilots started recovering equally quickly from all three ADI presentations. Bank angle was not used as a variable for analysis in the current experiment because of limitations on the recording software. Manual review of the data did not give us reason to suspect that different bank angles produced systematically different recovery results, but later experiments will have to confirm this. When asked about their preferences, nine pilots preferred the general aviation format, two the military, and one the commercial ADI.

Discussion

Roll reversal errors on the commercial ADI were almost 5 times more frequent than on the other two ADI's. Since there were no significant differences in response latency across the three different ADI presentations, pilots do not appear to engage in a speed-accuracy trade-off (cf. Gardner, 1954). That is, the much higher probability of roll reversal on the commercial ADI's is not preceded by a faster response time when faced with a commercial ADI presentation, which means the higher error rate stems from other sources. This large performance gradient, by pilots who actually use the commercial ADI in their daily practice, would point to the importance of the control-display compatibility principle in using the roll index for directing recovery action. Indeed, this result mimics the findings by Kovalenko (1991), that no amount of overlearning (all pilots tested in our study had a minimum of five years commercial ADI experience) can likely overcome the inherent incompatibility between required control action and display movement in the commercial ADI. Consistent with for example Roscoe (1968), we found that pilots not only performed better with an ADI that is not the one they use on a daily basis, but actually prefer one (in this study the general aviation ADI) that they do not use for their jobs, which in turn matches ADI research results by Browne (1954). The strong preference for the general aviation ADI strengthens our confidence in the primacy of the control-display principle in determining the success of roll recovery using the sky pointer (Indeed, the control-disply principle operates unambiguously in pitch—the other dimension of the ADI). Transfer effects (i.e. prior experience with the general aviation horizon) were compensated to the best of our ability by selecting pilots who had experience on all three ADI types.

An alternative explanation, however, would be that figure-ground confusion is less likely in the general aviation configuration. Linking the sky pointer to the aircraft symbol and having the rest move behind this fixed relationship (like the general aviation ADI does) could help lift the figure (airplane symbol) away from the blue-brown background, preventing the kinds of figure-ground confusions or reversals that have been claimed to distort commercial ADI's, where the roll index moves with the background, and not with the figure. If this were a dominant mechanism, however, we would expect to see worse performance on the military ADI (which also links pointer with horizon) as well, which was only slightly the case here after truncating the data set. This would suggest that potential figure-ground confusion at least does not help in resolving what part of the instrument to move which way. Yet more research would be necessary, especially in comparing older electro-mechanical and newer LCD ADI's, to identify the exact figure-ground mechanism in flying the artificial horizon.

The experimental set-up in our study of course lacked the kinds of natural cues that may be present in real roll reversal. Yet in instrument flying (whether military, commercial or general aviation) visual cues from the instruments are deemed the most reliable, and pilots are consistently taught to distrust other sources. In fact, it is the ADI, including the sky pointer, that is the primary instrument for attitude control and recovery. The presence of natural cues can often exacerbate spatial disorientation, rather than alleviating it (Gillingham, 1992), and indeed did not prevent the Saab 340 accident (FOCA, 2001).

Conclusion

While commercial "inside-out" artificials horizons are increasingly the Western norm, in the near future even in General Aviation, it almost consistently produces the worst roll recovery performance. In this study we highlighted the role of the sky pointer and found that the commercial set-up (roll index on top of the ADI, slaved to the horizon) is almost five times more likely to produce roll reversal errors than the military or general aviation configuration. The source of error probably lies in more basic features of the commercial ADI itself—the violation of the control-display compatibility principle being a strong contender on the basis of the results from our study.

We may need to re-think the format of LCD ADI's being introduced into general aviation. While these typically slave the roll index to the horizon, as in the commercial ADI, pilots' familiarity (and superior performance) with a sky pointer slaved to the aircraft symbol would create a much safer alternative, and one able to help prevent loss of control accidents in general aviation. For commercial aircraft we propose that the industry considers extending the Bank Angle Warning submode that is available as an option in GPWS (Ground Proximity Warning System) so that it could warn of roll reversal errors. Of course, adding an extra layer of technology to deal with a basic human factors shortcoming of a primary display would seem a little circuitous as countermeasure, and perhaps, after five decades of research, we could do better altogether (e.g. Singer, 2000).

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