# Flying by Ear: Blind Flight with a Music-Based Artificial Horizon

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Two experiments were conducted in actual flight operations to evaluate an audio artificial horizon display that imposed aircraft attitude information on pilot-selected music. The first experiment examined a pilot's ability to identify, with vision obscured, a change in aircraft roll or pitch, with and without the audio artificial horizon display. The results suggest that the audio horizon display improves the accuracy of attitude identification overall, but differentially affects response time across conditions. In the second experiment, subject pilots performed recoveries from displaced aircraft attitudes using either standard visual instruments, or, with vision obscured, the audio artificial horizon display. The results suggest that subjects were able to maneuver the aircraft to within its safety envelope. Overall, pilots were able to benefit from the display, suggesting that such a display could help to improve overall safety in general aviation.

## INTRODUCTION

Spatial disorientation for in-flight operations refers to a situation in which the attitude, airspeed, and altitude of the aircraft, relative to the earth, is misinterpreted by a pilot. This situation can arise from receiving impoverished or misleading information from visual, vestibular, and/or proprioceptive sensory systems, such as when a pilot's view of the horizon is obscured by clouds or darkness. Although this situation may be overcome by reference to visual instruments in the cockpit, conflicting information may be sufficiently compelling that the information provided in these visual instruments may come into question. A recent report from the Australian Transport Safety Bureau (Newman, 2007) suggests that 90-100% of all pilots will experience some level of spatial disorientation during flight operations. Yet, even these numbers may underestimate the true prevalence of this phenomenon, for many events go unreported by pilots and, of those incidents where spatial disorientation is believed to be the cause, many are fatal.

Because of the pervasive nature of spatial disorientation, and the potential severity of its consequences, it is desirable to provide to pilots additional information about the attitude of an aircraft that may complement (or substitute for) the visual artificial horizon display. However, because piloting is a visually intensive task, the incorporation of additional visual displays may simply increase visual workload. Thus, it is preferable to exploit the capabilities of another sensory modality such as audition. The auditory system is particularly well suited to the continuous monitoring of inputs and the detection and recognition of changes in those inputs that may occur over time. As such, providing continuously updated information about the attitude of an aircraft via auditory cues may allow a pilot to maintain an awareness of the aircraft attitude at all times.

Several researchers have attempted to develop an auditory display that can provide robust information about a number of flight variables to pilots including attitude, airspeed, rate of turn, and vertical velocity (DeFlorez, 1936; Forbes, 1946; Lyons, Gillingham, Teas, Ercoline, & Oakley, 1990; Grohn, Lokki, & Takala, 2004). In general, these studies have shown that an auditory display that provides orientation cues for pilots can be easily learned and can provide reliable and robust information that a pilot can utilize to maintain controlled flight. However, because these displays have employed relatively simple acoustic stimuli such as tones, noises, and tonal complexes, reports from participants in these studies have suggested that the displays themselves can lead to fatigue and annoyance, and thus may not be well toleratd by pilots, resulting in a situation in which pilots ignore or completely disengage the display.

To this end, a new audio artificial horizon display was developed that continuously imposes aircraft attitude information on an arbitrary audio input signal. Because it was undesirable to introduce additional audio into the pilot's headset, the signal upon which the attitude information is imposed is music that the pilot has selected. This is consistent with current flight operations in which pilots may listen to music via in-dash entertainment systems or MP3 players injected directly into aviation headsets. The music of the audio artificial horizon display can be attended to when desired, but relegated to the attentional "background" when not needed, thus suggesting it might be well suited to this application.

## METHODS

### Participants

Sixteen male pilots were recruited from the NASA Langley Research Center subject pool to participate in this study. In order to qualify for participation, pilots were required to be at least 18 years of age and possess a current private or commercial pilot certificate with an instrument rating and a high-performance endorsement/experience. In addition, pilots were required to have fewer than 3000 hours of total flight time, and were required to have performed at least three takeoffs and landings within the 90-day period immediately prior to these flight tests. Of these participants, four were military pilots in addition to maintaining private pilot status.

## Aircraft

The testbed for this experiment was the NASA Cirrus SR-22X high-performance general aviation aircraft (see Figure 1). This single-engine, four-seat aircraft has, in addition to the normal cockpit instrumentation, a custom air data and attitude/heading reference system (ADAHRS) to collect real-time data on a variety of in-flight variables such as GPS location, altitude, velocity and orientation. A windows-based PC was mounted in the aircraft for experimental control, and a suite of audio/visual recording equipment was used to record in-flight audio communications as well as multiple views of the in-flight operations.

Figure 1. Left panel: NASA's Cirrus SR-22X aircraft, used as the experimental testbed. Right panel: Subject pilot wearing vision obscuring goggles.

## Stimuli

The fundamental component of the audio artificial horizon display is a set of signal processing algorithms designed to add attitude information to an arbitrary audio input signal. Because the goal was to generate a display that was informative, tolerable, and did not increase perceived workload, musical material, selected by each individual subject pilot, was used as the basic stimulus. In order to impose attitude information on the music, the left and right stereo signals from the music were first summed to a monaural signal. This signal was then convolved with a custom set of filters using the SoundLab audio rendering package (Wenzel, Miller, & Abel, 2000). These filters - Attitude Indication Transfer Functions, or AITFs – imposed pitch- and roll-dependent attitude information on the music based on input obtained from the aircraft's ADAHRS via a real-time interface. The AITFs processed the signal such that the audio artificial horizon provided a reference that, like a visual artificial horizon instrument, indicated the direction the pilot was to maneuver the aircraft in order to return to level flight.

Aircraft roll was indicated by manipulating the interaural level difference of the signal in the headset. This was accomplished by attenuating the AITF in the ear ipsilateral to the direction of aircraft roll and simultaneously amplifying the AITF in the opposite ear, thus maintaining constant overall stimulus intensity independent of the angle of roll of the aircraft. The result was an audio signal that was lateralized to the side of the head corresponding to the higher wing of the aircraft, indicating the pilot should roll back to that side to become level with the horizon.

The pitch of the aircraft is indicated in the audio horizon display by manipulating three stimulus parameters. The first manipulation involves filtering the music such that the high frequencies are emphasized when the nose of the aircraft is pitched downward (using a shallow high-pass filter), and the low frequencies are emphasized when the nose of the aircraft is pitched upward (using a shallow low-pass filter). The slope of the filter varied from 0 dB/octave at the level-flight position to 6 dB/octave at the maximum safe pitch deviation. A second spectral emphasis is imposed on the music by adding a 'repetition pitch' to the signal. This approach imposes an apparent pitch on the stimulus at 1000 Hz when the aircraft nose is pitched upward, and 2400 Hz when the aircraft nose is pitched downward, even if the source signal does not contain energy in that frequency region. The use of spectral cues to indicate aircraft pitch was adopted because elevation cues in spatial audio displays often result in poor localization, particularly when they have not been customized for the individual user (Wenzel, Arruda, Kistler, & Wightman, 1993), and elevation cues may be severely disrupted in noisy cockpit environments (Gilkey, Simpson, Isabelle, Anderson, and Good, 1997). On the other hand, changes in auditory pitch can result in the perception of changes in vertical position (see, e.g., Pratt, 1930). Finally, an interaural decorrelation cue is imposed on the signal, the effect of which is to make the perceived auditory image more diffuse as a function of pitch deviation from level flight. The auditory image is maximally punctuate during level flight. The set of AITFs was designed such that the greatest changes in each of the dimensions described above (i.e., interaural level difference, apparent pitch, and image diffuseness) changed most rapidly in response to maneuvers near level attitude, and changed less rapidly in response to pitch and roll changes at more extreme attitudes. The values employed for these changes were determined from basic psychoacoustic studies in our laboratory. Note that because the salience of the auditory cues depends on the continuous presence of source material, it was important that this material remain relatively consistent in level throughout the flight. As such, subjects were encouraged to select material other than western classical music, which often has extended periods of reduced volume. Most opted for music classified as 'rock' or 'pop'.

The audio stimuli were sent to a 4-channel mixer, where they were combined with the audio signals from the aircraft intercom, and the output was sent to a set of stereo ANR headphones worn by the subject.

## Procedure

*General*. Before actual flight operations, a pre-flight briefing was provided, during which the experimental procedures were reviewed and the specifics of the audio horizon display were described. The subject pilot was then given an opportunity to interact with the audio horizon display using a custom-built, PC-based flight simulator in which attitudinal changes in the aircraft were reflected in the audio display.

Once all the appropriate safety briefings and procedures were completed, the subject pilot, safety pilot, and experimenter boarded the aircraft for the flight tests. All takeoffs and landings were accomplished by the safety pilot. However, once safely airborne, control of the aircraft was given to the subject pilot for additional familiarization with the audio display as well as the aircraft flight controls and dynamics. On all flights, the subject pilot was in the left front seat, the NASA safety pilot was in the right front seat, and the AFRL experimenter was in the back right seat, and all testing took place in an airspace approximately 30 miles from the NASA Langley Research Center. Each subject flew 2 1.5-hr sorties in day visual meteorological conditions (VMC) at 2000-8000 ft above ground level (AGL) at approximately 140 knots indicated air speech (KIAS). Two tasks were completed on each flight: (1) a waypoint-finding task designed to examine the utility of spatial audio displays for in-flight navigation (see Simpson, Brungart, Dallman, Yasky, Romigh, and Raquet, 2007) and a test of the audio artificial horizon display.

*Experiment 1: Identification of changes in aircraft attitude.* On the first of two sorties for each subject, an experiment was conducted in which the subject pilot, with vision obscured (see Figure 1) and control of the aircraft in the hands of the safety pilot, was required to identify a change in the attitude of the aircraft from level flight as quickly as possible. On each trial, the safety pilot altered the attitude of the aircraft in one axis only (i.e., pitch or roll) at a rate of approximately 1°/sec. As soon as a change in attitude was recognized, the subject was required to press a button on a response box and provide a verbal response identifying the axis and direction of change that had occurred (e.g., *roll left*). The verbal response and response time were recorded, and the safety pilot returned the aircraft to a level attitude before the start of the next trial. A total of 20 trials were run for each subject, 12 with an audio cue and, as a control, 8 with no audio cue (i.e., the subject had only G-loading, or 'seat-of-the-pants', information on those trials). Four trials were run in the audio condition, followed by four in the no-audio condition, and so on until all 20 trials had been completed.

*Experiment 2: Recovery from displaced attitudes.* On the second of two sorties, the ability of the subject pilot to use the audio artificial horizon display to recover the aircraft from displaced attitudes was examined. On each trial, the subject pilot's vision was completely obscured. The safety pilot maneuvered the aircraft into a displaced attitude, varying in both roll (±25° angle of bank) and pitch (±10° pitch). Once the desired attitude was achieved, the control of the aircraft was given to the subject pilot, and the subject pilot was required to recover the aircraft, in a smooth and controlled manner, to level flight using only the audio horizon display. The subject announced when he believed the recovery was complete, at which point the response time and attitude of the aircraft were recorded, and the safety pilot once again took control of the aircraft. Ten such trials were completed for each of 16 subjects, for a total of 160 trials. These trials were preceded by a control condition in which each subject performed 10 instrument recoveries. For these recoveries, subjects had a view of the cockpit instruments only. This test is a standard procedure required of pilots in order to obtain an instrument rating. If, during any recovery, the subject pilot maneuvered the aircraft beyond ±45° angle of bank or ±20° pitch, or the aircraft descended to an altitude less than 3000 ft mean sea level (MSL), the safety pilot took control of the aircraft and the trial was aborted.

## RESULTS AND DISCUSSION

### Experiment 1

Due to technical difficulties, data in the attitude identification task for four of the subjects were unavailable. Thus, the data reported for this task are from only 12 subjects.

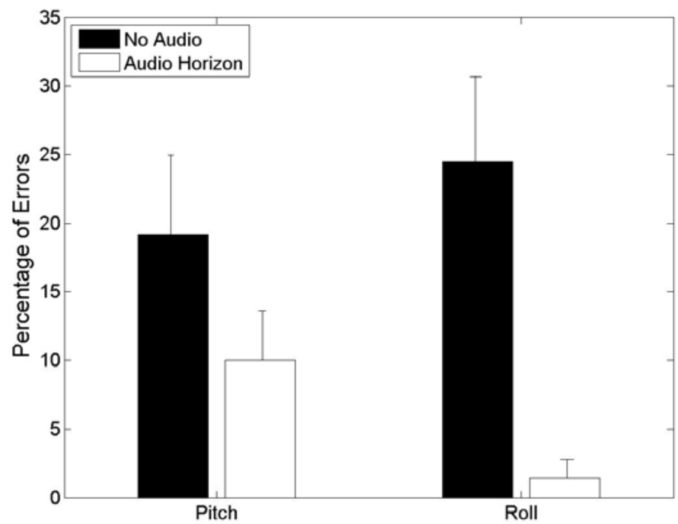


Figure 2. Mean percentage of errors for identification of axis and direction of aircraft attitude change. Black bars represent the 'No Audio' condition, where subjects had only proprioceptive cues; white bars represent data from trials in the 'Audio Horizon' condition. Error bars represent ± 1 standard error.

The percentages of errors (i.e., trials in which the subject incorrectly identified the axis and/or direction of aircraft attitude change) in the 'No Audio' and 'Audio Horizon' conditions are shown in Figure 2. As can be seen, there were relatively few errors overall, despite the fact that each pilot's vision was completely obscured. The greatest percentage of errors (24%) was obtained in the 'No Audio' condition when the subject was required to identify a change in the roll of the aircraft. When the audio horizon cue was provided, error rates dropped substantially for identifying changes in pitch (40%) and even more dramatically in roll (90%), suggesting that subjects were able to effectively utilize information in the display for attitude judgments.

Mean response times and angular change for correct attitude identification are shown in the left and right panels, respectively, of Figure 3. Consider first the 'No Audio' condition (black bars). As can be seen, subjects took less time to judge a change in aircraft pitch overall than in roll (left panel), and the amount of angular change necessary to correctly identify the aircraft attitude was smaller for pitch than roll (right panel). These results suggest that the subjects, with no information other than G-loading, were better able to identify changes in aircraft pitch than in than in roll. When the audio horizon display was provided (white bars), response times for identifying a change in aircraft roll substantially decreased (left panel), and the required angular change for identification was reduced (right panel). However, the opposite was true for identifying changes in pitch. Here, the addition of the audio horizon actually led to a slight increase in response times and required angular change for identification. Moreover, response times associated with pitch changes were substantially longer in the 'Audio Horizon' condition than for those involving roll changes.

**Experiment 2**

Figure 4 shows the mean value of the aircraft pitch and roll angles obtained at the completion of the recoveries in the 'Visual' condition (i.e., with an unobscured view of the visual instruments) and the 'Audio Horizon' condition (i.e., when the subject's vision was completely obscured). Note that the mean ending pitch value in the 'Visual' condition was not 0°, but rather approximately 5° pitch up.

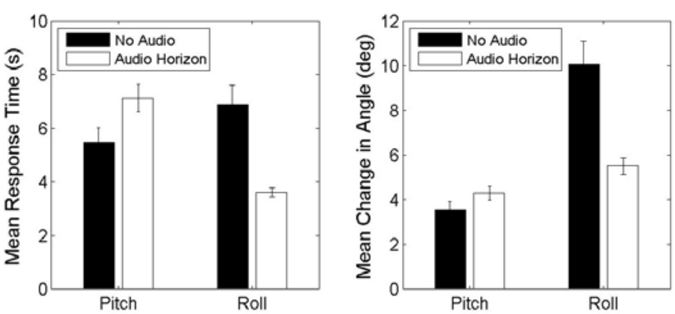


Figure 3. The left panel depicts mean time to identify the change in attitude of the aircraft. The right panel depicts the mean change in angle required for identification of the change in attitude. Data in each panel are shown for both pitch and roll. Black bars represent the 'No Audio' condition and white bars represent the 'Audio Horizon' condition. Error bars represent ± 1 standard error. Data represent only those trials in which a correct identification was made.

This 5° offset in ending pitch corresponds to the normal operating state of the Cirrus SR-22X aircraft, which typically requires a slightly positive pitch value to maintain a constant altitude in straight and level flight. Moreover, a comparison of the mean ending pitch values across conditions reveals that the end state of the aircraft in the 'Audio Horizon' condition was very similar to that in the 'Visual' condition (within 1°), suggesting that there was no systematic bias in the perceived attitude of the aircraft with the audio horizon cue.

A more meaningful measure of the performance of the audio horizon cue can be derived from an analysis of the variability of the starting and ending pitch and roll values. Ideal performance in this task would result in the pilot maneuvering the aircraft to the same pitch and roll state at the end of each recovery. Therefore, one measure of the effectiveness of the audio horizon is the extent to which the standard deviation in pitch and roll at the end of the trial is smaller than the standard deviation in pitch and roll at the start of each trial. Figure 5 compares the standard deviations for pitch and roll at the beginning and end of the recovery in the 'Visual' and 'Audio Horizon' conditions. The standard deviations within each axis were similar across conditions (approximately 18-21° in roll and 7-8° in pitch). These values reflect the variability in the initial state of the aircraft, which was randomly selected by the safety pilot on each trial. As would be expected, the standard deviations computed for the ending state of the aircraft were very small (1-2°) in the 'Visual' condition, presumably because pilots simply had to visually align the instruments with the desired end state of the aircraft. However, standard deviations for the ending state of the aircraft in the 'Audio Horizon' condition were substantially reduced as well relative to the values at the start of the trial. Specifically, standard deviations were reduced by roughly 70% in the roll dimension and approximately 40% in the pitch dimension. These results clearly show that the pilots were able to extract a substantial amount of pitch and roll information from the audio horizon in order to recover the aircraft from a displaced attitude.

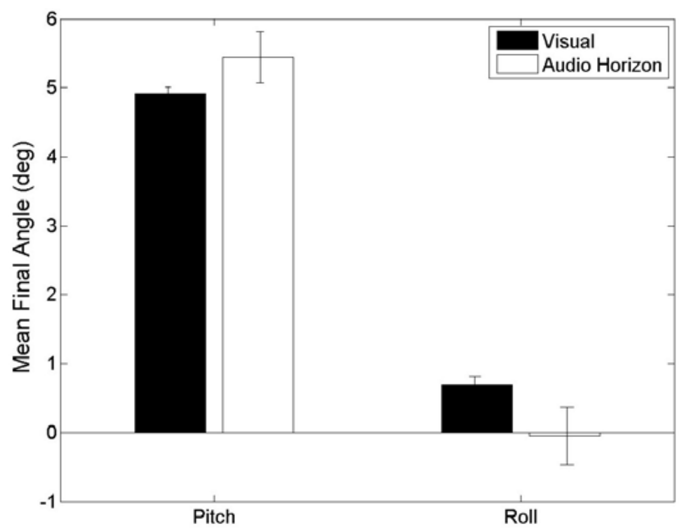


Figure 4. Mean values for attitudinal angles obtained at the completion of the recoveries from displaced attitudes. The black bars represent the 'Visual' condition and white bars represent the 'Audio Horizon' condition. Error bars represent ± 1 standard error.

Although it appears that subjects were able to recover the aircraft from displaced attitudes reasonably well using the audio horizon display, it is not expected that pilots would be able to use the display to achieve precise control over the pitch and roll of an aircraft. Rather, the primary goal of the display was to reduce spatial disorientation and reduce the chance that pilots would maneuver the aircraft out of its safe operating envelope. Therefore, one metric for evaluating the practical utility of the display is the percentage of trials in which the subject's initial maneuver after taking control of the aircraft was in the correct direction to achieve a safe attitude. The results from this analysis reveal that subjects made the appropriate initial maneuver in approximately 85% of the trials with the audio horizon display. Also notable is the fact that, across 160 trials tested in this task, only three trials (<2 %) were aborted as a result of the subject maneuvering the aircraft into an attitude that exceeded the safe operating limits - in nearly all trials with the audio horizon (92%) the aircraft attitude at the end of the recovery represented an improvement relative to the attitude at the onset of the trial. These results seems to indicate that although the subjects could not reliably maneuver the aircraft to exactly the desired pitch and roll values using the audio display, this display adequately supported the pilot in his efforts to maintain the aircraft within the safe operating envelope.

Finally, the times required by subjects to recover from displaced attitudes were found to be fairly different across conditions. Average time to recover in the 'Visual' condition was 10 sec, as compared to approximately 18 sec when using the audio artificial horizon. However, a closer look at the flight paths during the recoveries revealed that much of the additional time taken to recover in the 'Audio Horizon' condition was spent 'fine tuning' the aircraft at attitudinal values near the desired attitude.

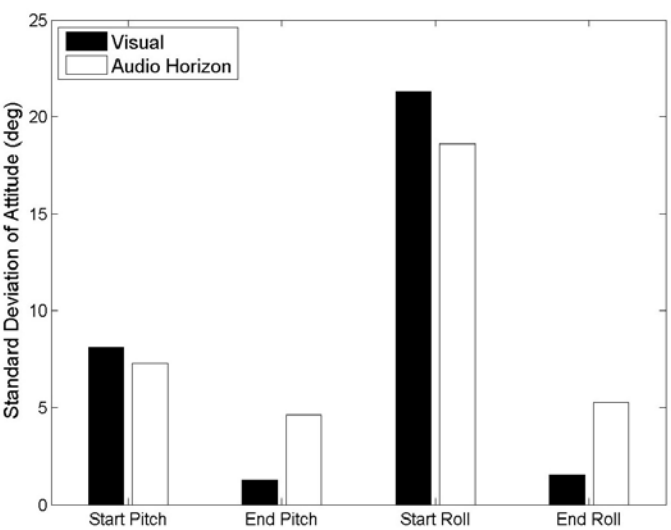


Figure 5. Standard deviations for the start and end pitch and roll values. The black bars indicate the 'Visual' condition and the white bars indicate the 'Audio Horizon' condition.

## CONCLUSION

In this paper, we have presented the results of an experiment that evaluated the effectiveness of a music-based auditory horizon cue for improving a pilot's situational awareness about the orientation of a general aviation aircraft. There are many challenges in the design of such a display, which makes no assumptions about the type of audio signal a pilot might wish to listen to and must work under the noisy conditions that typically occur in a maneuvering aircraft. However, on balance, the results from this study suggest that the candidate audio horizon display examined here was effective both in increasing the pilot's awareness about changes in the attitude of the aircraft, and allowed the pilot to maneuver the aircraft toward straight and level flight from a random starting position. The subjective impressions of the pilots were also very positive.

Nevertheless, there is also clearly room for improvement in the display. Many pilots reported that the pitch cues appeared less salient than the roll cues in the audio horizon. This is related to the fact that the current display was tuned to provide maximum resolution in pitch at pitch values near 0° rather than the +5° pitch value that actually corresponds to straight and level flight in the aircraft. We believe that even better overall performance could be achieved by modifying the pitch display such that it is centered on this +5° value.

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