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Three-Dimensional Audio Versus Head-Down Traffic Alert and Collision Avoidance System Displays

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The advantage of a head-up auditory display for situational awareness was evaluated in an experiment designed to measure and compare the acquisition time for capturing visual targets under two conditions: standard head-down Traffic Alert and Collision Avoidance System (TCAS) display and three-dimensional (3-D) audio TCAS presentation. (The technology used for 3-D audio presentation allows a stereo headphone user to potentially localize a sound at any externalized position in 3-D auditory space). Ten commercial airline crews were tested under full-mission simulation conditions at the NASA–Ames Crew-Vehicle Systems Research Facility Advanced Concepts Flight Simulator. Scenario software generated targets corresponding to aircraft that activated a 3-D aural advisory (the head-up auditory condition) or a standard, visual–audio TCAS advisory (map display with monaural audio alert). Results showed a significant difference in target acquisition time between the two conditions, favoring the 3-D audio TCAS condition by 500 ms.

The current implementation of the Traffic Alert and Collision Avoidance System (TCAS II) uses both auditory and visual displays of information to supply flight crews with real-time information about proximate aircraft (Air Transport Association Flight Systems Integration Committee, 1989). However, the visual display is the only component to convey spatial information about surrounding aircraft, whereas the auditory component conveys no

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spatial information and is generally used to bring attention to the visual display.

Within its standard implementation, three categories of visual–aural alerts are activated by TCAS, contingent upon an intruding aircraft's distance (see Figure 1). The first category, an informational visual display, presents *proximate traffic.* In this case, TCAS functions more as a situational awareness system than as a warning system. The second category, a visual–aural cautionary alert, is a *traffic advisory* (TA). The threshold for activating a TA is a potential conflict within 40 sec; an amber-filled circle is generated on a visual map display, and an auditory warning consisting of a single cycle of the spoken words, "TRAFFIC–TRAFFIC," is given. The third category, a visual–aural warning alert, performs as a *resolution advisory* (RA). The threshold for activating a RA is a potential conflict within 20 sec to 25 sec; a red-filled square is generated on a visual map display, and an auditory warning annunciating the appropriate evasive action necessary (e.g., "CLIMB–CLIMB–CLIMB") is given.

Chappell et al. (1989) evaluated the effectiveness of TCAS during a full-mission simulation experiment. Three TCAS conditions were evaluated, each involving a different level of visual–aural information about the location of conflicting aircraft. In addition, a non-TCAS condition was evaluated in which only spoken traffic advisories from air traffic controllers (ATC) were used. Their measure of performance focused on the time to make an evasive maneuver in response to a TCAS RA. The findings suggested that, although the TCAS displays are superior to the non-TCAS display, no significant benefit is gained in increasing the complexity of the TCAS display itself. Specifically, no advantage was found in providing pilots with a head-down planform display of traffic information. Perrott, Sadralodabai, Saberi and Strybel (1991) found that adding spatial auditory information can significantly reduce the acquisition time necessary to locate and identify a visual

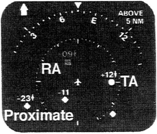

FIGURE 1 Standard TCAS visual symbology. The proximate traffic symbol is shown on an actual display as a white-filled diamond, the TA is shown as an amber-filled circle, and the RA as a red-filled square.

target. They used a 10 Hz click train from a speaker that was either spatially correlated or uncorrelated to a target light. The results showed that spatially correlated information from an auditory source substantially reduced visual search time (between 175 and 1,200 ms).

In an experiment by Sorkin, Wightman, Kistler and Elvers (1989), localization accuracy rather than target acquisition time was studied in a simulated cockpit environment. A magnetic head tracker was either correlated or uncorrelated with a 3-D audio display that corresponded to the locations of visual targets. Results of the study found that accuracy of azimuthal localization was improved when head movement was correlated with the 3-D audio display but that elevation localization was no better than chance.

Begault (1993) evaluated the effectiveness of a 3-D, head-up, auditory TCAS display during a full-mission simulation by measuring target acquisition time. All crews used visual out-the-window search in response to a TCAS advisory and no planform display was used. Half the crews used the standard audio alert and half used an alert that was heard over headphones and spatialized using 3-D sound techniques. The direction of the spatialization was linked to the target location, but the spatialized audio stimuli were exaggerated by a factor of three in relationship to the visual angle to facilitate head movement in the aurally guided visual search (e.g., a visual target at 10° azimuth would correspond to a spatialized stimulus at 30° azimuth). Results of the study found a significant reduction in acquisition time when using spatialized sound (4.7 sec vs. 2.5 sec). In the current experiment, 3-D sound was also used for aurally guided visual search but the exaggeration factor was not included.

In our study, we evaluated the feasibility of using either a head-down visual display (standard TCAS) or a head-up audio display (3-D TCAS). Two groups consisting of five crews were evaluated during a full-mission simulation. It was hypothesized that a significant difference in both acquisition time and the number of targets acquired might occur between the two conditions.

METHOD

Participants

Ten two-person flight crews served as participants for this study. Crews were composed of airplane pilots employed by a major U.S. air carrier and were rated in a glass cockpit aircraft (e.g., Boeing 757, 767, 737–300/400, or 747–400). Each crew member was paid a nominal amount for participating. Because all crew members had current medical certificates, they had been previously evaluated for normal hearing within the last year (first officers) or six months (captains) by company and Federal Aviation Agency medical examiners.

Experimental Design

Two groups, each comprising five two-person crews, were evaluated in a between-subjects design. The standard TCAS group used an audio–visual system approximating the standard TCAS system currently implemented in U.S. commercial air carriers. This consisted of an audio TA presented via an overhead speaker and a standard TCAS head-down map display. The 3-D TCAS group wore stereo headsets and were presented a binaurally processed version of the audio portion of the TA but were not supplied with any visual system information. The perceived direction of the 3-D auditory advisory was adjusted to correspond to the azimuth of the target outside the window.

The 10 crews were assigned randomly to either the standard TCAS or the 3-D TCAS group. The dependent variables were (a) the time interval between the appearance of a visual target in conjunction with an aural advisory and the verbal response from a crew member indicating acquisition of the target and (b) the number of targets acquired.

The crew members were instructed to call out verbally when they had visually acquired the aircraft outside the window (a consistent utterance, "Got it!"). Calculation of acquisition time (the difference between the time the visual target was generated and the beginning of the verbal utterance) was enabled by the use of a coordinated time code, used for both the scenario computer that activated the visual targets and the vertical interval time code (VITC) that was marked on a video/audio tape of the crew recorded for each flight segment. The video tape also was marked digitally from the scenario computer at the time a visual target was activated, because the out-the-window view could not be seen in the video. An unbiased researcher "rocked" the video tape to the point at which the first verbal utterance from either the pilot or first officer could be heard and then noted the VITC time code for that video frame. The target activation time was then subtracted from this value to determine the acquisition time for that particular target. The accuracy of determining the beginning of the verbal utterance was within two video frames (0.066 sec). Each verbal acquisition increased the count for the number of targets acquired. Target acquisition times and the number of targets acquired were also categorized according to whether the target was visible to both or to only one crew member.

Stimuli

A total of 24 targets were presented to the crews for evaluation during the cruise phase of the flight. Six additional targets were included as "dummy" targets to provide a realistic context for the TCAS system in the vicinity of the airports (3 during takeoff and 3 during landing phases of flight) but were not included as part of the experiment's data set (although pilots were required to respond in the same manner as to the other targets). The reason these 6 targets were not analyzed was the expectation of a relatively high amount of variability between crews during takeoff and landing phases of flight (e.g., workload, air traffic control communications). Also, in the vicinity of the airports (but not during the cruise phase of flight), simulated city lights were visible, making the out-the-window scene difficult to control across crews. The relative luminosity and contrast ratios between modeled airport data and the targets would otherwise be an uncontrolled variable in acquisition time; crews approach airports in a slightly different manner and time.

In order to assure that each target had a consistent size, all targets were fixed at a 3-mile distance from the aircraft. This made the target appear as a flashing dot of light similar to that seen out of the cockpit window of a real aircraft. However, the target did not change size from the perspective of the participants, because its position was always linked to the position of the simulator aircraft; in other words, it visually appeared to remain at a fixed distance and identical speed to the simulator. This was done to eliminate movement of the target as a variable and to eliminate differences between crews as a function of movement of the aircraft.

The out-the-window positions of the targets formed a 3 × 8 matrix (see Figure 2). Elevation of the targets were randomly assigned within the three visual angles: 5 targets at 3,000 ft above the pilots' ship at −50°, −37°, −22°, −10°, 10°, 22°, 37°, and 50° azimuth; 14 targets at the same relative azimuth but at the same elevation as the pilots' ship; and 5 targets at the same relative azimuth but at 3,000 ft below the pilots' ship.

For the standard TCAS condition, a computer generated four to six moving symbols depicting proximate aircraft. The symbols appeared at pseudorandom positions and were presented on the TCAS map display. One of the symbols would be elevated to advisory status for target acquisition evaluation, and the remaining symbols would eventually vector off the display.

Available Field of View

A substantial limitation inherent in all flight simulators is the available out-the-window field of view for each pilot. The simulator used in this experiment was a modified Lockheed–Georgia cockpit equipped with a Link–Miles Image II visual system. This system had a three-channel, four-screen display. Each channel contained a discrete display of visual information relevant to the scenario; the two center screens in the simulator displayed an identical visual scene from one channel, with one screen visible by each pilot. The center channel screen allowed each pilot a field of view extending to approximately ±25° azimuth. In addition, two side screens fed by the other two channels gave each pilot a unique side field of view that extended the total field of view to approximately ±52° azimuth.

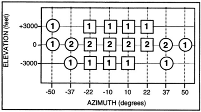

FIGURE 2 The relative elevations and azimuths of the 24 targets used in the experiment. The number indicates the frequency of occurrence; the squares indicate targets visible to both crew members.

Figure 3 shows the available field of view for the captain; the first officer's view was the mirror image of this figure. Note that the field of view from 25° to 52° was available to only one crew member, whereas the area between ±25° was available to both crew members.

Figure 4 shows the vertical field of view. The immediate range is from approximately −13° to +16°, but can extend from −18° to +20° with head and body adjustments. For reference, the visible range of a target at 3 miles is shown in terms of relative elevation (in feet) above and below the simulator.

3-D Sound Processing

The aural alert consisted of a nonspeech preadvisory and a voiced "TRAFFIC–TRAFFIC" advisory similar to that used in normal TCAS systems. The preadvisory consisted of two brief (66 ms) complex tones (labeled BIP–BIP in Figure 5) separated by 39 ms of silence. These were synthesized by adding multiple square waves with different fundamental frequencies and giving the overall composite a rapid amplitude envelope rise time to favor the conveyance of spatial information. Because of the rich harmonic structure, it could be played at a level approximately 10 dB below the speech alert and still be noticeable. The TCAS speech alert (labeled TRAFFIC–TRAFFIC in Figure 5) was digitally recorded by a male speaker in a soundproof booth using an electrostatic microphone, preamplifier, and a digital audio tape recorder.

The total duration of the alert was 1.36 sec: 171 ms for the preadvisory, a 85-ms silent interval, 462 ms for the word "TRAFFIC", a 180-ms silent interval, and another 462-ms "TRAFFIC" (see Figure 5). This recording was transferred to a desktop computer using audio recording software and hardware at a sampling rate of 50 kHz. Next, the aural alert was convolved with head-related transfer function (HRTF) measurements.

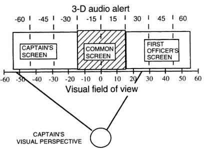

FIGURE 3 The mapping between the horizontal field of view in the simulator and 3-D audio cues from the perspective of the left seat (captain's position). The lower scale indicates the continuous visual field of view, which is about −52 to 25° maximum for the captain's seat. The upper scale labeled "3-D audio alert" and the vertical dashed lines show how the continuous visual field of view was categorized into eight possible azimuth alerts. The screens upon which the targets were simulated are indicated for reference. There were two common screens, one for each crew member; about 5° of the first officer's screen can be seen by leaning out from the normal seating position.

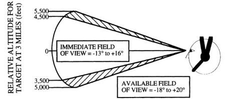

FIGURE 4 The vertical field of view in the simulator, based on the relative altitude of an aircraft at 3 miles' distance.

HRTF convolution is a filtering method for imposing 3-D audio cues on an input sound source. Simply put, the effect of the pinna and head shadowing (or equivalent simulation of these effects by HRTF convolution) results in perceptually significant cues for auditory spatial location. These cues can be captured and then subsequently manipulated by the designer of an auditory display. (Additional information on 3-D audio techniques for auditory displays can be found in Begault, 1994; Blauert, 1983; and Wenzel, 1992. 3-D audio methods related specifically to aeronautical applications are discussed in Begault & Wenzel, 1992, and Doll, Gerth, Engelman, & Folds, 1986).

The aural alert was convolved with HRTF measurements to simulate 12 spatial auditory positions: left 15°, 30°, 45°, and 60° azimuth, 0° elevation (for the visual targets at eye level elevation, at −10°, −22°, −37°, and −50°, azimuth, respectively); the same azimuths at 54° elevation (for the visual targets at 3,000 ft above eye level, at approximately 15° elevation); and the same azimuths at −36° elevation (for the visual targets at 3,000 ft below eye level, at approximately −15° elevation). Positions for right 15°, 30°, 45°, and 60° azimuth were obtained by reversing the output channels at playback, resulting in a total of 24 available spatialized positions (8 for each azimuth, as shown in Figure 3). The elevation cues were exaggerated relative to the actual visual positions, because psychoacoustic evidence suggests that elevation judgments are often compressed relative to the actual target positions when listening through nonindividualized HRTFs (Wenzel, Arruda, Kistler, & Wightman, 1993; Wightman & Kistler, 1989)

The convolution was performed in nonreal time on a desktop computer by supplying formatted versions of the HRTF measurements and the aural alert to a software signal processing package (Longley, 1990). The resulting signals were then converted to a 33.3 kHz sample rate in 12-bit, signed, integer form and subsequently stored in a stereo audio sampler (Yamaha

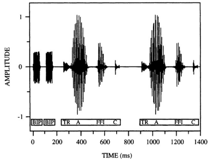

FIGURE 5 Arrangement of the prealert and traffic enunciation used for TCAS advisories in the experiment.

TX–16W). The stimuli were played back in coordination with the scenario software via note on/off commands inherent to the musical instrument digital interface (MIDI) specification. Further information on MIDI and spatial processing can be found in Begault (1994).

Each pilot wore a stereo headset (Sennheiser model HME–1410–KA, modified for stereo) that was selected for comfort and fidelity. The headphone frequency response ranged between 20 Hz and 18 kHz and weighed 250 g. The headset had a supra-aural design (the drivers rested on the outside of the ears), allowing outside conversation to be monitored more easily than with a circumaural design. Playback of the speech portion of the alert was at approximately 74 dB SPL at the ear; the simulator's ambient background noise was approximately 70 dB (C weighting) measured in the center of the cockpit with an omnidirectional microphone during the cruise phase of flight. The spectrum of the ambient sound was approximately that of white noise (for wind simulation) combined with engine sound simulations.

Procedure

Training. Each crew spent 2 days at the simulator, with the first day and a half devoted to familiarization and training. The training period focused on the particular handling capabilities of the aircraft, the touch screen displays, controls, electronic checklist, and procedures to be used. It also included a brief demonstration of the 3-D audio system for the five crews using that system. This consisted of a 2-min demonstration of several targets accompanied by the 3-D audio traffic alert. No other information was given to the pilots about the nature of the experiment.

Scenario. The two-person crews flew the experimental flights on the afternoon of the second day. The experiment was conducted during the cruise phase of the fourth and final leg (San Francisco International Airport–Los Angeles International Airport). The first three legs of the scenario were considered practice and, therefore, were excluded from the analysis. The 24 targets were designed to occur at an approximate rate of 1 every 3 min during the cruise phase of flight (more than 15 miles from departure or destination). Each individual target was activated according to the distance in miles from the destination. During the experiment, all normal operations were realistically simulated, including conventional VHF Omni-Directional Radio (VOR) navigation and communications with ATC (ground, tower, approach, departure, and center). Complete darkness was simulated, with approximately 50 miles visibility throughout the flights. Crews were instructed to follow their normal company standard operating procedures as closely as possible.

RESULTS

A target was considered to have been acquired if the crew obtained it within a 10-sec time window, which is the limit before the traffic could potentially be elevated to traffic resolution status in a real situation. Only two targets were acquired outside this time window and were, therefore, excluded from the analysis.

Based on the examination of acquisition time, a total of 20 outliers (acquisition times > 3 *SDs*) were found. The standard TCAS group had 7 outliers, 2 of these being extreme outliers (±5 *SDs*), whereas the 3-D TCAS group had 13 outliers, 1 of which was extreme. All outliers greater than 3 *SDs* were excluded from the analysis. These outliers appeared in a random manner among crews and condition and did not correlate with specific targets.

A two-way analysis of variance (ANOVA) with acquisition time as the dependent variable was conducted. This analysis (Condition × View) was conducted to determine if significant differences existed between targets in the field of view available to both crew members versus an individual's field of view. The ANOVA revealed a significant main effect for condition (3-D vs. standard TCAS groups), $F(1, 187) = 15.09$, $p < .0001$, as well as a significant main effect for view, $F(1, 187) = 50.37$, $p < .0001$, although there was no interaction present, $F(1, 187) = 1.76$, $p > .05$. These results are shown in Figures 6 and 7.

An additional ANOVA (Condition × Elevation) was conducted to determine if there were significant differences in target acquisition time for targets at the aircraft's elevation versus targets from above and below (i.e., those that fell into the upper or lower horizontal sections of the grid shown in Figure 2). This analysis also showed a significant main effect for condition, $F(1, 187) = 11.19$, $p < .001$, but no significant main effect for elevation, $F(1, 187) = 1.01$, $p > .05$, or interaction present $F(1, 187) = 0.11$, $p > .05$; see Figure 8.

An additional set of analyses were conducted using the number of targets acquired as the dependent variable. The mean number of targets acquired for the standard TCAS group was 19.4 ($SD = .95$), whereas the mean for the 3-D TCAS group was 18.2 ($SD = .95$). There were no significant main effects or interactions for these analyses, although there was approaching significance for elevation, $F(1, 219) = 3.65$, $p < .06$.

DISCUSSION

An important finding from this experiment implies that the presence of a spatial auditory cue can significantly reduce the time necessary for visual search in an aeronautical safety environment; the mean acquisition time for the standard TCAS group was 2.63 sec ($SD = .19$), whereas the mean for the

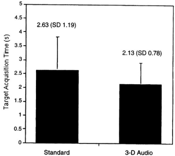

FIGURE 6 Mean target acquisition times and standard deviations for the 3-D audio and standard TCAS groups.

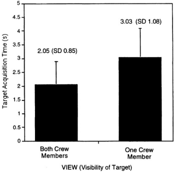

FIGURE 7 Mean target acquisition times and standard deviations for targets visible to both crew members (−22°, −10°, 10°, and 22° azimuth) compared to targets visible to only one crew member (−50°, −37°, 37°, and 50° azimuth).

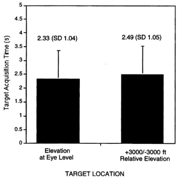

FIGURE 8 Mean target acquisition times and standard deviations for targets at eye level (0° relative to the pilots' ship) compared to those targets at ±3,000 ft relative to the pilots' ship.

3-D TCAS group was 2.13 sec (*SD* = .78). This result is in line with the studies of Perrott, Saberi, Brown and Strybel (1990) and Perrott et al. (1991), which found advantages for aurally guided visual search in the cockpit, using analogous conditions in the laboratory. Although 500 ms may seem to be a modest improvement, it does suggest that, in an operational setting, an aural 3-D TCAS display may be desirable in addition to a standard TCAS display. This is because pilots can keep their head "out the window" looking for traffic without needing to move the head downward to the planform map display and then back up. In other words, by accessing an alternative perceptual modality—sound—the visual perceptual modality is freed to concentrate on other tasks if necessary. In an actual cockpit with 3-D sound added to the current TCAS system, the pilot flying could use the auditory information for immediate head-up search while the pilot not flying could gain numerical altitude information and verify the direction for the other pilot.

Begault (1993) evaluated 3-D and monaural traffic alerts in a similar experiment but without use of a head-down map display. In this experiment, the spatialized positions were exaggerated in relation to the visual display by a factor of 3. Spatialization of the aural alert resulted in a decrease in the mean target acquisition time from 4.7 sec to 2.5 sec. Both Begault's result and the current data suggest that spatial processing of an auditory alert is useful for guided visual search; in other words, aural alerts have greater potential in human–machine interfaces than to function merely as "attention getting" mechanisms. Begault suggested the use of the exaggerated auditory azimuths may have contributed to the faster acquisition times for the 3-D display. The mean target acquisition time of 2.5 sec (SD = .8) in Begault's experiment was actually slightly slower than that found in this experiment (M = 2.13 sec, SD = .78), suggesting that exaggerated auditory stimuli are not necessary for effective aurally guided visual search.

Unlike actual cockpits, the field of view in the simulator is such that the person sitting on the left side cannot see beyond 25° to the right, and the person on the right side cannot see beyond 25° to the left. So it is possible that the spatial auditory cue was used in estimating target positions in a crude way to transcend the limitations of the simulator environment (i.e., if it sounds to the right, the first officer searches; and if it sounds to the left, the captain searches). This is indicative of a task delegation procedure. However, in actual operations contexts, search is usually conducted most actively by the pilot not flying, depending on the context of the phase of flight and the relative urgency of the TCAS alert. Even if this trade-off feature were not an element, the spatial auditory cue could still have been utilized as a crude way for determining where to begin visual search. If it is true that the spatial sound cue provides a general direction for search that is subsequently refined by visual search, then the additional azimuthal accuracy provided by a head-coupled, 3-D auditory display (Sorkin et al., 1989), is probably unnecessary.

Overall, the results presented here must be evaluated provisionally, particularly for the reason that a simulator's field of view is not at all equivalent to that in an actual aircraft in spite of the substantial efforts to ensure realism. Parallel explorations of aurally guided visual search should continue to be evaluated under controlled laboratory conditions and then compared to research under simulated flight operations. An additional factor not evaluated here is the fact that out-the-window targets can move quickly across the field of view; the work by Strybel, Manligas, and Perrott (1992) on evaluating the minimum audible movement angle is particularly relevant in this regard.

IMPLICATIONS FOR FURTHER RESEARCH

Because of the need for evaluation under actual flight conditions, our future experiments for evaluating a 3-D audio TCAS system will more than likely involve the augmentation of a standard TCAS system, as opposed to replacing the visual display with an audio display as described here. At the same time, the observation by Billings (1991) that a harmonious "integration of information does not mean simply adding more elements to a single display" should be heeded. In other words, 3-D audio should not merely add clutter to the visual–auditory display offered by existing TCAS systems but, instead, should complement the existing system in a specific way (e.g., to be activated under circumstances when visual resources are under heaviest demand).

An example of how a 3-D audio display would complement the existing TCAS system might be in a situation in which more than one RA or TA is received in close temporal succession. As characterized within the multiple-resource model of Wickens (1992), the division of attention between an auditory and visual modality for two channels of information is often preferred to two visual or two auditory channels by themselves. Tasks interfere more with each other (in the sense of "time-sharing" attention between the two tasks) when resources are shared intramodally, as opposed to bimodally. The 3-D auditory display effectively transforms the verbal portion of the TCAS TA ("traffic–traffic") into a carrier for both spatially and verbally coded information. In theory, one could segregate multiple TCAS events ("channels") in an optimal manner by using the current visual display for TAs, proximate, and other traffic and the 3-D audio system for only RAs. According to the multiple-resource model, the occurrence of an RA and TA that occur in close temporal succession might be better handled by the pilot with such a system, as opposed to the current system. Future experiments may show that the 3-D audio TCAS display provides a similar target acquisition time advantage for RAs as for TAs, a situation where the .5-sec advantage might be most welcome, but this remains to be seen. In a related experiment, we are currently examining a similar 3-D audio display for a ground collision avoidance system, for use under low visibility conditions (Begault, in press).

A final consideration for eventual application is that crew members would be required to wear stereo on-the-ear headsets. The difficulty may be in breaking old habits associated with the insert earpiece style of headset (e.g., the Plantronics MS–50, which has been in use since the mid-1960s), but the fact that a 3-D auditory display can be combined with active noise cancellation may be a boon for those pilots concerned or who should be concerned with permanent hearing loss. Provisionally, it is possible to report that most pilots had no problem with intercockpit conversation while using on-the-ear headsets in the simulator; a future study will report on the headset issue in more detail.

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