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Hear me flying! Does visual impairment improve auditory display usability during a simulated flight?

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Abstract

Sonification refers to systems that convey information into the non-speech audio modality [1]. This technique has been largely invested in developing guidance systems for visually impaired individuals. In 2008, more than 140 systems of this type used in various application areas were referenced [2]. In aeronautics, such a system –namely the Sound Flyer– is currently used by visually impaired pilots in real flight context to control the aircraft attitude. However, it is unclear if this system would be acceptable for sighted individuals. Indeed, early visual deprivation leads to compensatory mechanisms which often result in better auditory attentional skills [7, 8]. In the present study we assessed this issue. Two groups of pilots (blind vs. sighted) took part in a flight simulator experiment. They were all blindfolded to avoid potential visual information acquisition (i.e. some blind individuals had residual visual capacities). Participants had to perform successive aircraft maneuvers on the sole basis of auditory information provided by the sound flyer. Maneuvers difficulty varied with the number of parameters to apply: easy (none), medium (one: pitch or bank) or hard (two: pitch and bank). The Sound Flyer generated a pure tone (53dB SPL) modulated as a function of pitch (tonal variation) and bank (inter-aural and rhythmic variations). We assessed flight performance along with subjective (NASA-TLX) and neurological (irrelevant auditory-probe technique; [9]) measures of cognitive workload. We hypothesized that the automatic cerebral reaction to deviant auditory stimuli (10% "ti" among 90% "ta"; 56db SPL) would be affected by the difficulty [10, 11] and participants' auditory attention. Preliminary data analyses revealed that blind and sighted participants reached target-attitudes with good accuracy (mean error of 2.04°). Globally, subjective cognitive workload and brain responses to the auditory probe were influenced by the difficulty of the maneuver but not by the visual impairment. These initial results provide evidence that auditory displays are effective, not only for maintaining straight and level flight [6], but also for attaining precise aircraft attitudes. Results also suggest that flight maneuvers should remain quite simple to avoid too high cognitive workload. In other words, attitude sonification can provide robust information and, along with Brungart and Simpson [3] specifications, could contribute to the fight against spatial disorientation in the cockpit.

Keywords: Auditory display, aeronautics, mental workload, usability, irrelevant-probe technique

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1. Introduction

All sonification systems are designed with a common aim: to process some relevant data and to turn it into an intelligible auditory stream. Given the pervasive property of the auditory modality, these systems are often used in situations where the continuous monitoring of critic information might be impossible due to attentional (e.g. visual overload) or sensory (e.g. visual impairment) limitations. These techniques have been largely invested in developing auditory guidance systems devoted to the blind. In 2008, 140 systems of this type were referenced in various application areas [2]. In aeronautics, such an auditory display, namely the *Sound Flyer,* has been developed and is currently used by visually impaired individuals in real flight contexts. On receiving and processing auditory information about the aircraft attitude, these pilots gain steering and decision-making autonomy in the cockpit. They are able to fly the aircraft and to maintain the desired attitude via an audio-stream consisting in sound modulations (pitch, rhythm, inter-aural balance). Upon request, an additional speech synthesis gives indication on important flight parameters (altitude, speed etc.). Interestingly, beside these successful developments, other studies have suggest that auditory displays could also be used by unimpaired people to exert some control over their aircraft attitude to follow a flight plan [12, 13]. More recently, Brungart and Simpson [3] have proposed that even a simple attitude sonification could help facing spatial disorientation issues in the cockpit, the leading cause of fatal aviation accidents (15 to 69%; [4]). During these episodes, pilots often fail to sense correctly the spatial position of the aircraft because they receive incomplete or competing information from their visual, vestibular or proprioceptive systems [5]. In the worst case, the compelling dimension of this conflict can confuse pilots and even to disengage them from the visual instrumentation. To that extent, auditory redundancy of critical parameters (e.g. pitch and bank) via an auditory display would represent a valuable safety net against spatial disorientation. It would provide additional non-visual cues of the aircraft spatial orientation and could help to remove visual-vestibular ambiguity. An open question is whether the usability of such a system in a complex man-machine interface would be acceptable for the auditory attentional capacities of sighted individuals. As a matter of fact, it has been pointed out that early visual deprivation led to compensatory cerebral mechanisms (i.e. plasticity) often resulting in better auditory attentional skills [7, 8]. In this study we investigated the extent to which the Sound Flyer usability would be affected by auditory attentional skills. It is worth answering this question as the introduction of an attitude sonification system in the cockpit should not impair auditory processing capacities. In particular, it should preserve the ability to detect unexpected critical auditory events such as alarms.

1.1. Auditory attention and visual impairment

Numerous studies have provided evidences of brain plasticity — the brain adaptive capacity to reorganize itself at a structural and functional levels [14]. This reorganization relies on links between primary sensory brain areas [15] that favor the processing of *available* sensory inputs. In the early blind, literature provides evidence of this brain reorganization, especially at the occipital area which is normally responsible for visual processing. Although it does not receive any visual sensory input, it benefits non-visual information processing such as auditory or tactile processes. For instance, in the blind, performance during a simple sound localization task is positively correlates with activation in the occipital cortex [14]. This occipital recruitment is thought to directly enhance some complex operations such as selective or divided auditory attention [7, 8]. Kujala et al. [24] showed that cerebral reaction to unexpected auditory events was less attention-dependent in the blind than in the sighted. These results indicate that blind individuals can have better performance with auditory displays and shall be less impaired in their ability to process additional unexpected critic stimuli such as auditory alarms. Indeed, the brain has to remain distractible even when focusing on a specific channel of information. In the present experiment, we used the irrelevant auditory-probe technique to assess the openness of the attentional system of pilots while using the Sound Flyer.

1.2. The irrelevant auditory probe technique

When attempting to evaluate the cognitive demand of a task, one might probe the participant with a secondary task. For instance, one might ask the participant to monitor for a specific stimulus in a sound stream, while performing a primary task. Generally, performance for this irrelevant secondary task is thought to reflect the amount of resources left by the task of interest, thus indicating its ongoing demand [16]. This has been largely corroborated at the cerebral level, where some ERP parameters were found to be sensitive to allocation of processing resources. In particular, the N1 and the P3 components elicited by primary and secondary tasks stimuli were shown to vary in amplitude, as a function of perceptual and central processing resources respectively [17], thus providing a valuable workload index. However, as the secondary-task method forces the performing of an irrelevant task, it can penalize mental workload assessment and interpretation. Not only it increases the overall workload, but also it can interfere with the primary task, thus resulting in artificial decrease of performance at the task of interest [18]. Furthermore in an ecological context, one might want to assess mental workload without disturbing the natural course of the operator activity. To address these limits, Papanicolaou and Johnstone [9] proposed the "*irrelevant-probe* technique": a paradigm in which participants are still probed with oddball sounds but do not have to overtly respond to them. Assuming that available resources are automatically devoted to additional stimuli processing, ERP reactions to stimulations shall reflect the amount of processing resources left by the task at hand [18]. In particular ERP components amplitude for rare compared to frequent sounds, is supposed to be related to momentary shifts of attention toward unexpected events, even though not requiring any response. In 2008, Allison and Polich [11] showed that, during a difficulty-varied video-game, most ERP components (P2, N2 and P3) of a response to a rare tone decreased as the difficulty of the video-game increased, whether this rare tone had to be responded to or not.

1.3. Experimental goal and hypothesis

In this experiment we further investigate auditory display usability in aeronautics. Two groups of pilots (blind *vs.* sighted) had to achieve precise maneuvers (e.g. "turn left 5 degrees") that varied in difficulty, on the sole basis of the auditory information provided by the Sound Flyer. There were two main objectives. First, we evaluated the possibility to extend the use of the Sound Flyer to normal sighted pilots in order to provide a robust support for spatial orientation, especially in sighted pilots who might suffer from critic visual-vestibular illusions. Secondly, we tested whether the introduction of such a display in the cockpit would impair auditory attention toward other rare auditory events, i.e. distractibility toward unexpected sounds. We conducted behavioral measurements of the flight performance and subjective (NASA-TLX) and objective (irrelevant auditory-probe technique) measurements of mental demand. Because of their presupposed better auditory attentional capacities, we expected blind pilots to show better overall performance as well as a better auditory distractibility while maneuvering. Then, we thought that increasing maneuver difficulty would impair distractibility toward unexpected events.

2. Method and Materials

2.1. Participants

9 visually impaired and 4 sighted pilots participated in the experiment (mean age 39.9, range 22-60, 6 females). All pilots have signed a consent form and were controlled for their auditory acuity, using AudioConsole software and Silento Supermax headphones. Because blind pilots use the Sound Flyer in real conditions, they were more familiar with the system than the sighted pilots, and it was difficult to control for familiarity.

2.2. PEGASE Flight Simulator

The experiment took place aboard the PEGASE simulator (Fig. 1). It simulates a twin-engine aircraft flight model and reproduces angular acceleration along three-axis (roll, pitch, and height). Participants sat in the pilot's seat (front-left) of the aircraft. To prevent any use or interference from the visual sense, even with residual capacities, all participants were blindfolded.

2.3. The Sound Flyer

Aircraft sonification was supported by a simplified version of the Sound Flyer (Thales, France), where auditory information was restricted to pitch and bank aircraft attitude values. The sonification consisted in modulating a pure-tone as a function of pitch and bank. The pitch of the pure-tone being strictly correlated to the pitch of the aircraft so that any one-degree pitch variation of the aircraft led to a step in the tone-pitch. The aircraft bank being transposed by the inter-aural balance and the rhythm of the tone. As the aircraft turned left/right, the tone moved progressively from the center (O°) to the left/right (2°) of the auditory scene and its rhythm became faster as the aircraft bank get stronger (5° steps). Upon request, participants were able to ask indication on pitch and bank that was given by a speech synthesis triggered by a two button RB530 Cedrus response box placed under the pilot's right hand.

2.4. Irrelevant auditory-probes stimuli

During all experimental scenarios, irrelevant-probe stimulation (i.e. passive oddball) was composed by frequent (90%) and rare (10%) syllables (/Ta/ or /Ti/). Each difficulty condition included 27 rare and 143 frequent probes. Probes sequences were randomly generated on a trial-to-trial basis with two successive rare probes being separated by at least two frequent probes. Time interval between two syllables ranged between 800 and 1200 milliseconds. Frequency-syllables mapping (e.g. rare-/Ti/ or rare-/Ta/) was counterbalanced across subjects.

2.5. Aviation Task

The maneuvers to perform were indicated to the participant at the onset of each trial by mean of a synthetic voice. Pitch-target values were chosen from the set {3°, 5°, 10°} × {Up, Down}; bank-target values were chosen from the set {5°, 10°, 20°} × {Left, Right}. Instructions and irrelevant auditory-probes stimuli were handled by a Matlab script (Psychtoolbox) and were mixed with the Sound Flyer sonification *via* a Gemini PS-540i mixing table. The resulting auditory scene was displayed to the participant in intra-auricular headphones.

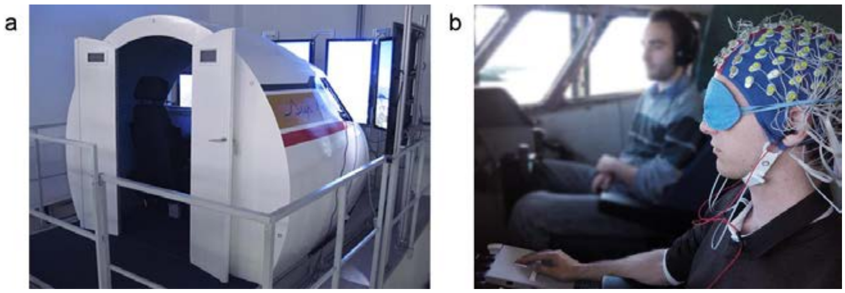

Fig. 1. (a) The PEGASE simulator; (b) a participant in the pilot's seat

2.6. Procedure

After having signed up a consent form, participants performed an auditory acuity test, in a calm and isolated room. Then, participants were given instructions for the experiment while we equipped them with the 128-channel electroencephalography head-cap. They were then invited to sit on the pilot's seat (front-left) of the simulator and were equipped with a blindfold and the intra-auricular headphones. Experimenter sat on the copilot's seat (front-right). Participants were told they would have to reach precise aircraft attitude, on the sole basis of auditory information. After what they were explained the sound flyer functioning, i.e. the relationship between the aircraft attitude and the variation of the sound. On average, a session lasted two hours and a half.

2.7. EEG recording and processing

EEG data were recorded with a 128-channel Active Two Biosemi system, at a 2048 Hz sampling rate and decimated at 512 Hz before further processing. The data were re-referenced to the average of the left and right mastoids, and filtered with a band-pass of 0.1-30 Hz. Using EEGLAB [19], an ICA was performed to identify and remove ocular artifacts. Data were then segmented in 1100 ms epochs, starting 200 ms before the onset of each active phase (baseline). Individual ERPs and grand averages were computed using EEGLAB.

2.8. Subjective workload

After having rid the participants from their equipment, we used a French paper and pencil version [20] of the NASA-TLX [21] to evaluate subjective workload for each difficulty level. The NASA test was composed of six dimensions to which participants attributed a score comprised between 0 (i.e. minimum demand for this dimension) and 100 (i.e. maximum demand for this dimension). Dimensions were *mental demand, physical demand, temporal demand, performance, effort* and *frustration level*. Only the score to the *performance* dimension was reversed. The overall subjective workload consisted in the average of all dimension scores. If they wanted to, they could also write down their comments about the experiment before the end of the session.

3. Results

3.1. Performance

For a given maneuver, flight performances were the absolute error between successive aircraft positions and the target-position. Only the parameters that were relevant to a maneuver were included in this calculation. For example, performance for bank parameter was not included in trial performance if the current maneuver concerned only the pitch parameter. Average error for the whole participants was 2.04 degrees, with standard error of the mean (SEM) = 0.31. A repeated-measure analysis of variance (ANOVA) revealed a significant difference in mean-error across the three difficulty levels, $F(2, 22) = 21.82$, $p < .001$, $\eta^2 = 0.66$. A post-hoc Tukey's HSD test showed that only low-difficulty condition (M = 0.65, SEM = 0.19) differed significantly from the others two difficulty conditions ($p < .001$) for both pairings. In contrast, medium-difficulty condition (M = 2.74, SEM = 0.51) and high-difficulty condition (M = 2.74, SEM = 0.31) pairing did not show significant difference ($p = .99$). This mean-error was greater for the blind group (M = 2.25, SEM = 0.37, n = 9) than for the sighted group (M = 1.57, SEM = 0.55, n = 4), although this difference did not reach a significance level, $F(1, 11) = 1.03$, $p = .33$. Finally, there was no interaction effect between group and difficulty to explain performance variation, $F(2, 22) = 1.30$, $p = 0.29$.

3.2. Subjective workload

Subjective workload varied significantly across the 3 levels of difficulty as revealed by a repeated-measures ANOVA, $F(2, 22) = 37.15$, $p < .001$, $\eta^2 = 0.77$. A post-hoc Tukey's HSD test revealed that differences between paired conditions were also significant: subjective workload for the low-difficulty condition (M = 10.65, SEM = 3.76) was significantly smaller than for the medium-difficulty condition (M = 28.65, SEM = 3.32, $p < .001$) which was significantly smaller than for the high-difficulty condition (M = 45.00, SEM = 3.89, $p < .001$). Workload evaluation was not impacted by the group, regardless of the difficulty, $F(1, 11) = 1.67$, $p = 0.22$. Likewise, there was no significant interaction between group and difficulty to explain workload scoring, $F(2, 22) = 2.74$, $p = .09$.

3.3. Event-related potentials

ERP analyses were focused on FCz electrode. Regardless of the group, N1 and P3 components showed greater amplitude for rare oddball syllables compared to frequent syllables. This difference was significant ($p < .05$) in a time windows comprised between 108 and 178 milliseconds for the N1, and between 380 and 420 milliseconds for the P3 (Fig. 2a). When considering all the participants, N1 amplitude for rare oddball sounds differed significantly between easy and other difficulty conditions ($p < .05$) in a time windows comprised between 112 and 174 milliseconds (Fig. 2b). No significant difficulty effect was observed on the P3 amplitude. Furthermore, these ERP components were not sensible to medium *versus* high difficulty variation.

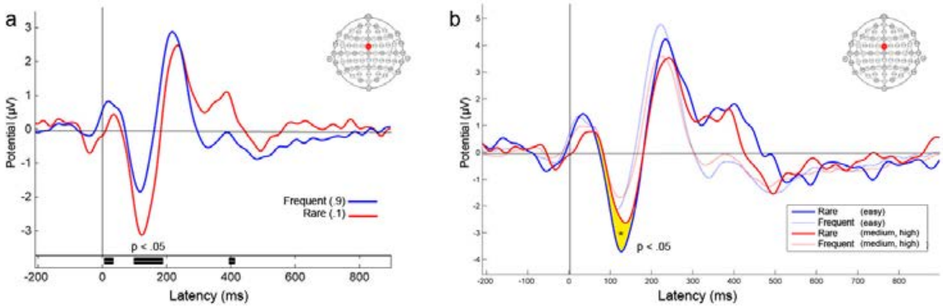

Fig. 2. (a) Mean ERP at FCz for frequent versus rare irrelevant-probe auditory stimuli, (b) Mean ERPs at FCz for rare and frequent irrelevant-probe stimuli, comparison between easy and other difficulty conditions.

4. Discussion

The present study aimed to evaluate the Sound Flyer usability, especially in the sighted pilots who often suffer from spatial disorientation. We also wanted to test whether the use of such a display would impair auditory attention toward other rare auditory events. Two groups of pilots (blind vs. sighted) performed auditory-guided maneuvers (e.g "turn left 5 degrees") which varied in difficulty. Along with behavioral performance measurements, we conducted subjective (NASA-TLX) and objective (irrelevant-probe technique) workload measurements.

4.1. Auditory display and spatial orientation

The first finding of this experiment was that the pilots reached targeted attitudes with a good precision (≈2 degrees), even when they were not familiar with the Sound Flyer, which was particularly the case of the sighted individuals. Given the relatively low precision provided by the Sound Flyer, i.e. 1 degree for pitch and 5 degrees for bank, this result constitutes evidence that pilots processed accurately auditory information to exert control over their aircraft attitude. More precisely, they were able to attain various hazardous positions starting from a level flight. This completes the previous evidence that auditory information could be used to fly an aircraft in a stable manner [12] and to rapidly recover a level flight from various hazardous positions [6].

Furthermore, we evaluated how the difficulty of the maneuvers would impact the usability of the Sound Flyer. On the one hand, performance for the low-difficulty condition differed significantly from the other two difficulty conditions. Let's recall that the easy condition was similar to a control condition, in which we asked participants to maintain a standard position (i.e. neutral attitude) all along the trial. Thus, it is not surprising that this condition triggered a better performance. On the other hand there were no differences in performance between the medium and high difficulty conditions, although participants reported a greater subjective workload for the high than for the medium difficulty condition. This showed that, even more demanding maneuvers did not exceed capacities of the pilots although it effectively varied the level of subjective workload as suggested by the result from the NASA-TLX questionnaire. Moreover, performance did not significantly varied between the blind and the sighted, suggesting that sighted pilots were fast at learning and processing effectively the auditory information. These results indicate that the auditory information was successfully used, even by sighted pilots, to support their aircraft spatial orienting.

4.2. Mental workload and auditory distractibility

If auditory display usability lies in its capacity to support a satisfying control over the aircraft attitude, auditory processing should not impair other critical processes, such as alarm monitoring. To test the impact of auditory processing on distractibility, we assessed workload by subjective and neurological means. We were particularly interested in N1 and P3 components, which denote perceptual and central stages of processing respectively [18]. Importantly, NASA-TLX scoring was sensitive to the difficulty levels. The more parameters were to apply, the higher was the workload scoring. This confirmed that the different conditions induced different levels of demand.

N1 component. Compared to the low-difficulty condition, amplitude of the N1 for rare tones was reduced in medium and high difficulty trials, suggesting a diminution of the available attentional resources in these conditions. Interestingly, ERP for frequent tones were not concerned by this difficulty effect, i.e. N1 amplitude was modulated by task demand only for unexpected auditory events. This suggests that Sound Flyer processing diminished the sensory gating dedicated to novel sounds, reflecting an early attentional filter mechanism [22].

P3 component. On the other hand, we did not obtain any difficulty effect for the P3 component. This was consistent with Kramer et al. [10] who showed that when irrelevant, P3 amplitude to rare tones was not affected by the difficulty of the primary task. This insensitivity might be due to the passive dimension of the probe. Participants were instructed to ignore these “added sounds”, so that rare tones processing could have been aborted prior to the full evaluation of the stimulus, regardless of resources availability at stimulus onset [10]. Moreover, P3 component is thought to be composed of at least two sub-components: with P3a being related to stimulus-driven reorienting of attention and P3b to goal-driven context-updating [23]. Here, the passive instruction might have led extinction of the P3b component, because context-updating of oddball rare tones was totally irrelevant to the activity.

5. Conclusion

The presented results are preliminary and have several limitations. The two samples that were included in this first analysis were different. The sighted sample was very small (n = 4) and it was impossible to evaluate its normal distribution. Furthermore, visually impaired people sample was more heterogeneous, showing greater variability in performance than the sighted sample ($SD_{blind} = 1.28$ vs. $SD_{sighted} = 0.31$), so that presently, it remains difficult to assess the effect of the group over the auditory display usability.

As a conclusion, the main proposal of this study is that auditory usability cannot be restricted to a performance analysis, especially in aeronautics where the auditory modality deserves critical events monitoring. Here, we showed that in spite of a good orientation performance, the Sound Flyer processing could mitigate perception of unexpected stimuli, especially at early stages of processing, and that this dimension of usability should be taken into account in further works about auditory display in aeronautics.

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