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Can an aircraft be piloted via sonification with an acceptable attentional cost? A comparison of blind and sighted pilots

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ABSTRACT

In the aeronautics field, some authors have suggested that an aircraft's attitude sonification could be used by pilots to cope with spatial disorientation situations. Such a system is currently used by blind pilots to control the attitude of their aircraft. However, given the suspected higher auditory attentional capacities of blind people, the possibility for sighted individuals to use this system remains an open question. For example, its introduction may overload the auditory channel, which may in turn alter the responsiveness of pilots to infrequent but critical auditory warnings. In this study, two groups of pilots (blind versus sighted) performed a simulated flight experiment consisting of successive aircraft maneuvers, on the sole basis of an aircraft sonification. Maneuver difficulty was varied while we assessed flight performance along with subjective and electroencephalographic (EEG) measures of workload. The results showed that both groups of participants reached target-attitudes with a good accuracy. However, more complex maneuvers increased subjective workload and impaired brain responsiveness toward unexpected auditory stimuli as demonstrated by lower N1 and P3 amplitudes. Despite that the EEG signal showed a clear reorganization of the brain in the blind participants (higher alpha power), the brain responsiveness to unexpected auditory stimuli was not significantly different between the two groups. The results suggest that an auditory display might provide useful additional information to spatially disoriented pilots with normal vision. However, its use should be restricted to critical situations and simple recovery or guidance maneuvers.

1. Introduction

Sonification is commonly defined as the systematic, reproducible, and objective data-dependent generation of non-speech sounds (Kramer et al., 1999; Hermann et al., 2011). It aims to provide an auditory representation of data in order to convey meaningful information from a dataset to a listener via an auditory display (or sonic interface). Any sonification system must meet certain criteria: the sound has to reflect properties and/or relations in the input data; interactions between data and sound must be accurately defined; it must be reproducible, i.e. two identical datasets must produce structurally identical sounds and it must allow the processing of various datasets (Hermann, 2008). Sonification techniques have been employed in various application areas such as exploration of data (Delogu et al., 2010; Degara et al., 2014; Rutz et al., 2015), process monitoring (Neuhoff et al., 2000; Hermann et al., 2003) or assistive technology for the visually impaired (Kay, 1974; Edwards, 1989; Auvray et al., 2007; see Roentgen et al., 2008 for a review). In all these situations, sonification is generally needed since the continuous monitoring of critical visual information might be impossible due to attentional (e.g., vision is necessarily engaged in another direction) or sensory limitations (e.g., visual impairment).

In aeronautics, such a sonification system, namely the soundflyer, is currently used by visually impaired people. This embedded system operates the sonification of two dimensions of the aircraft attitude, i.e. its pitch and its bank angles. The pitch angle of an aircraft corresponds to the angle between its longitudinal axis

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and the horizontal plane. For instance, when an aircraft's nose is up, its pitch angle value is positive. The bank angle of an aircraft corresponds to the angle between its wings (or its lateral axis) and the horizontal plane, when viewed from the rear. The sound-flyer sonification consist in modulating the features (i.e. frequency, rhythm, inter-aural balance) of a sinusoidal pure tone which is continuously displayed to the pilot via his headphones. The pitch of the aircraft is rendered by the frequency of the pure-tone sound and the bank angle is rendered by the conjunction of the rhythm and the inter-aural balance of the sound (see section 2.2, for more details). The sound-flyer also contains a vocal module: upon request via a customized keyboard, speech synthesis can read aloud important flight parameters such as altitude, speed, vertical speed, and so on. Thanks to this system, visually impaired pilots gain monitoring and decision-making autonomy in the cockpit; they have less need to communicate with their co-pilot to access aircraft parameters. Beside the successful development of this system, used by blind pilots in real situations, laboratory studies have suggested that auditory displays could also be used by sighted pilots to exert some control over the attitude of their aircraft or to follow a given route (DeFlorez, 1936; Lyons et al., 1990; Brungart and Simpson, 2008). In particular, Brungart and Simpson (2008) have proposed that it could favor the orienting of the aircraft during spatial disorientation episodes, which are responsible for numerous fatal aviation accidents (Newman, 2007).

1.1. Facing spatial disorientation in the cockpit

Spatial disorientation occurs when a pilot is unable to determine the spatial position of the aircraft relative to the surface of the earth, because incomplete or competing information are coming from his visual, vestibular or proprioceptive systems (Benson, 1999). In the worst case, the compelling dimension of this perceptual conflict can lead pilots to neglect and mistrust their visual instrumentation. As such, it has been proposed that auditory redundancy of the aircraft attitude (e.g., the pitch and the bank values) could represent a valuable safety net against spatial disorientation (Brungart and Simpson, 2008). It would provide additional non-visual cues of the aircraft attitude and could help to overcome such perceptual conflicts. However, given the suspected higher auditory attentional capacities of blind people, the possibility for sighted individuals to use a sonification system remains an open question. One has to ensure that its use would remain acceptable for the auditory attentional capacities of sighted pilots, as highlighted in the Sonification Report (Kramer et al., 1999). In other words, in the context of a usability analysis, it is worth assessing whether the processing of a sonification system can interfere with other critical operations. In particular, it should not alter the ability of the brain to remain distractible (i.e. responsive to stimuli unrelated to the task at hand), especially in the cockpit where rare but possible critical auditory warnings may occur.

1.2. Auditory attention and visual impairment

There is a large body of evidence showing that the loss of vision or audition induces compensatory mechanisms in the remaining sensory modalities (Merabet and Pascual-Leone, 2010). Psychophysical and neuroimaging studies in both animal and human subjects have demonstrated that sensory deprivation from early developmental stages leads to functional reorganization of the brain that favors the spared modalities (Rauschecker, 1995). Such crossmodal compensation of perception is accompanied by functional reorganizations (Kujala et al., 2000) expressed as a colonization of the deprived cortical areas by the remaining modalities. In humans, brain imaging studies in blind individuals have revealed that the deprived visual cortex can be activated by auditory or tactile inputs (Sadato et al., 1996; Cohen et al., 1997; Weeks et al., 2000; Röder et al., 2002; Renier et al., 2013) thus reducing its alpha (8–12 Hz) oscillatory activity (Noebels et al., 1978; Leclerc et al., 2005; Kriegseis et al., 2006), indexing its idling state (Başar et al., 1997). Moreover, cross-modal compensation in blind people is strongly suspected to favor selective or divided auditory attention (Kujala et al., 1997; Collignon et al., 2006). For instance, Kujala et al. (1995), in an auditory-tactile task, showed that cerebral reaction to unexpected auditory events was less attention-dependent in the blind compared with the sighted. Participants in their study were presented with deviant (10%) and standard (90%) stimuli for each sensory modality. Standard and deviant stimuli differed from one another in their spatial locus of origin. They were asked to count the number of deviant stimuli for a specific sensory modality (auditory or tactile) and to ignore the ones in the other modality. Event-related potentials (ERP) for frequent and rare stimuli were recorded for the attended and the unattended sensory modalities. The results showed that the mismatch negativity component (indicative of the automatic cerebral reaction to deviant stimuli) was greater for the blind subjects compared with the sighted—*whether these stimuli were attended to or not*.

These results suggest that in cross-modal situations, blind individuals could exhibit better performance at auditory processing and might be less impaired in their ability to process additional unexpected stimuli. However, in the context of the present study, these results have to be qualified for at least two reasons. First, these studies were carried in very fundamental frameworks and do not allow to predict the effects of cross-modal compensations in more ecological situations. Indeed, many other factors such as task complexity or expertise, might interfere. Then, blind-sighted differences are often observed in response times (Kujala et al., 1997; Collignon et al., 2006) or in mismatch negativity amplitudes (e.g., Kujala et al., 1995), but not in accuracy level (see Collignon et al., 2006, p.177, for instance). Yet, in ecological situations one might find that performance is better defined by response accuracy than by a 100 ms reaction time difference. Thus, although cross-modal compensation in blind subjects is beyond doubt, it remains difficult to draw a straight prediction regarding its consequences on subjects performance, in an ecological piloting situation – which reinforces the importance of the present investigation.

1.3. The irrelevant auditory probe technique

In order to evaluate the cognitive demand of a task, one might probe the participant with a secondary task (Wickens, 1991). For instance, the participant can be asked to pay attention to a specific stimulus in a sound stream while performing a primary task (see Giraudet et al., 2015a for a recent example). Generally, performance of the irrelevant secondary task is thought to reflect the amount of resources left by the task of interest, thus indicating its ongoing demand (Wickens et al., 1983). This has been largely corroborated at the cerebral level, where some ERP components were found to be sensitive to the amount of available resources (Giraudet et al., 2015a). In particular, the N1 and the P3 components elicited by primary and secondary tasks stimuli often vary in amplitude, as a function of perceptual and central processing resources respectively (Kok, 2001), thus providing a valuable workload index. However, as the secondary-task method forces the participant to perform an additional irrelevant task, it can penalize mental workload assessment and interpretation. Not only does it increase the overall workload, but it can interfere with the primary task, resulting in an artificial decrease in performance at the task of interest (Ullsperger et al., 2001). Furthermore, in a real flight context, one might want to assess mental workload without disturbing the