Electrophysiological correlates of inattentional deafness: no hearing without listening

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Abstract

The analysis of airplane accidents reveals that pilots sometimes purely fail to notice yet critical auditory alerts. This inability of an auditory stimulus to reach consciousness has been recently coined under the term of inattentional deafness. Recent data from literature tend to show that tasks involving high perceptual load consume most of attentional capacity, leaving little for processing any task-irrelevant information. In addition, there is a growing body of evidence for a shared attentional capacity between vision and hearing. In this context, the numerous displays in cockpits are likely to produce inattentional deafness. A simplified piloting task was conceived, in which participants were required to make decisions based on complex visual indicators while continuous electroencephalographic (EEG) measurements were performed. During the task, a tone was played, either standard, which participants were told to ignore, or deviant ("the alarm", probability = 0.10) which participants were told to report. Preliminary behavioural results showed that up to 30% of deviant sounds were not detected. The analysis of EEG showed that a drastic diminution of the auditory P300 amplitude was concomitant with the occurrence of the inattentional deafness phenomenon. Applications concern integrative online prevention of alarms omission, mental workload measurements and enhanced warning designs.

Introduction

In aeronautics, the use of auditory alarms is widespread. Although one cannot question their efficacy (Wheale, 1981), they seem to come with some limitations (Edworthy et al., 1991). Many accidents are indeed due to pilots failing to react to the triggering of an auditory alarm (Bliss, 2003). An explanation is to consider the role of the sustained perceptual and attentional processes engaged in the cockpit. There is evidence that tasks involving high perceptual load consume most of attentional capacity, leaving little or none remaining for processing any additional information (see Lavie, 1995). Consequently, high-load contexts tend to prevent the perceptual processing of task-irrelevant information and facilitate various forms of inattentional blindness (Mack & Rock, 1998). This propensity to remain unaware of unexpected though fully perceptible stimuli is not limited to vision, however. Indeed, there is evidence that unexpected salient sounds can remain unnoticed under attention-demanding settings (e.g., Spence & Read, 2003; Fuchs et al., 2010;

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Hughes et al., 2012; Wood & Cowan, 1995). Although less well-known than its visual counterpart, this inattentional deafness phenomenon (Koreimann et al., 2009) is likely to have important consequences for safety-critical situations such as military or commercial flights as pilots are often overloaded with visual information. Yet the classical view of shared attention hypothesizes is that each sensorial modality owns a separate pools of resources. Hence, two tasks from different modalities (e.g. auditory and visual) should not interfere with each other (Wickens, 2002). However, this view could be partially unfounded as a growing body of literature provides evidence of attentional abilities shared between visual and auditory modalities (Brand-D'Abrescia & Lavie, 2008; Santangelo et al., 2007; Sinnett et al., 2006).

Interestingly, Macdonald and Lavie (2011) demonstrated that participants involved in a visual discrimination task were subject to inattentional deafness. Occurrences of inattentional deafness were even greater when the visual task involved a high level of perceptual load compared to low perceptual load. Under the assumption that attentional resources are shared between vision and hearing, it appeared that engaging in a task under high visual load may lead to a decline in the probability of processing an auditory stimulus. Therefore, a parallel can be drawn with aeronautics, where cockpit displays obviously generate a high perceptual and mental load. Lavie's load theory (1995) would henceforth predict that the primary task, i.e. piloting, would engage most of attentional resources. Few resources would consequently be available for processing additional information such as an unexpected auditory alarm, facilitating the inattentional deafness phenomenon.

Uncovering the neural correlates of inattentional deafness

The brain activity involved in processing auditory information has been particularly studied using Electroencephalography (EEG) techniques to measure Event-Related Potentials (ERPs). P300, one of the most commonly studied ERPs, is known to be induced by oddball paradigms that consists in the detection of an attended and unpredictable target stimulus (Polich, 2007). It reflects cognitive and attentional processes between 300 and 500 ms post-stimulus (see Hansenne, 2000, for a detailed review). When attentional focus deviates from the target, the P300 amplitude significantly decreases (Singhal et al., 2002). Therefore, P300 seems an excellent candidate to determine whether an auditory stimulus has broken through the attentional barrier. While several studies have revealed that auditory P300 amplitude may be lowered in audio-visual dual-tasks compared to auditory task alone (Armstrong & Singhal, 2011; Ramirez et al., 2005; Singhal & Fowler, 2004; Wester et al., 2008), the association between the inattentional deafness phenomenon and P300 has never been investigated.

Objective and hypotheses

Two main objectives were set during this work. Firstly, contrary to Macdonald and Lavie study (2011) in which only one occurrence of the inattentional deafness phenomenon was successfully reproduced (in their experiment, further attempt failed due to the impact of the pre-exposure to the sound), we aimed at designing an experimental paradigm allowing a sufficient number of occurrences of the inattentional deafness phenomenon within each participant to perform ERPs. Secondly, we intended to measure the inattentional deafness rate considering several visual/mental load conditions and to examine the possible concomitance between inattentional deafness and P300 modulations. For this purpose, we performed EEG measurements during a simplified but plausible aviation decision-making task in which participants were asked to take into account both visual and auditory signals. Auditory signals were based on the oddball paradigm to enhance the P300.

Our hypothesis was that an increase in visual/mental load should provoke a decrease in the alarm detection rate (deviant sounds) and a concomitant reduction of the P300 amplitude, suggesting that increased visual/mental load directly affects the cerebral response to an auditory stimulus, providing physiological explanation regarding the inability of pilots to perceive auditory warnings in the cockpit during critical flight phases.

Method

Participants

Sixteen male right handed healthy volunteers (mean age = 20.9 years, SD = 1.22) were recruited at ISAE Supaéro for this study. All participants were French undergraduate students, none of them had a history of neurological disease, psychiatric disturbance or substance abuse, or was under psychoactive medications. They were given full information about the experiment protocol and all gave their informed consent. Of these, one was excluded because his error rate in the control trials was above 15%. The 16 participants went through the same procedure, which began with a fatigue assessment using Pichot’s fatigue scale. Participants having a score over 22 would have been excluded, considered excessively tired. Then they performed the Paced Auditory Serial Addition Test (PASAT) to assess their working memory. No participant obtained a prohibitive score during this test (below 35% for the PASAT 3’’ or below 23 for the PASAT 2’’). Finally they completed a laterality test to confirm they were right handed.

EEG recordings and pre-processing

EEG data were recorded continuously with a Biopac EEG system. Before the experiment, a 19-electrodes cap (CAP100C) was placed on the participants’ head. 7 electrodes were analysed, distributed throughout the brain volume: Fz (frontal), Cz (central), Pz (parietal), T4 and T7 (temporal), O5 and O18 (occipital). The Biopac was connected by parallel cable to the experimental computer in order to mark trial onsets on EEG data. Three electro-oculographic electrodes (EOG) were placed on the left, on the right and above the eyes to record the muscular eyes activity. Artefacts created by eyes movements were removed online from the cerebral signal with Acqknowledge 4.0 EOG artefacts removal function.

Tasks

Two different tasks were presented: a decision-making task, called the landing task, and a classical oddball task. The oddball task was performed according to three experimental conditions: 1) during a low-load landing task (visual load = 1), participants simultaneously performed the oddball task and the landing task at a low load level; 2) during a high-load landing task (visual load = 2); 3) in the baseline oddball session were no parallel task was performed (load = 0), as in the classical oddball paradigm. Differently from Macdonald’s design, participants were asked to report it each time they heared the tone was a alarm. This way, the phenomenon of inattentional deafness could occur more than once on the same participant. First, participants went through the dual task session, performing both the landing task and the oddball task at the same time. Low and high load trials of the landing task were interspersed throughout the session. Then they completed the baseline oddball session, performing only the oddball task to give us their nominal response to the auditory stimuli.

The baseline oddball session. Participants performed the oddball task, consisting in a set of 200 trials in which 200 tones were played. Each trial presented a first time window lasting 2 to 4.5 second during which the tone was played, followed by a 2 seconds response time window, during which participants had to make their response if they noticed a deviant tone. Continuously during the session, a white noise at 50dB was played. During each trial, a 30dB tone was randomly played (between 500 milliseconds after the beginning and 500 milliseconds before the end of the first time window) during 150 milliseconds. This tone was either standard (frequency = 1900Hz, $p = 0.8$) or deviant (frequency = 1950Hz, $p = 0.2$), according to the oddball paradigm. To report their awareness of a deviant tone, participants pressed the central button of a three buttons response box. No response was to be given when the standard tone was played. The 2 seconds response window elapsed regardless of whether a response was made. Percentage of reported deviant tones was the dependant variable.

The dual task session. Participants were submitted to a set of 400 trials, during which they simultaneously performed both the oddball task and the landing task. In each trial, a 2 to 4.5 seconds video was displayed, followed by a 2 seconds response time window, during which participants had to make their response. During the videos (see figure 1), various indicators appeared on a screen: heading, magnetic declination, wind and score, which were fixed during the video, and the two ILS (Instrument Landing System) moving cursors, one vertical and the other horizontal. This video was followed by a 2 seconds response window, as during the baseline oddball session. During this response window, all indicators were frozen and still displayed on the screen. To answer correctly to the landing task, participants had to decide whether the landing was possible or not, according to rules shown in figure 2, based on the final values of the indicators at the end of the video, by pressing a button on a response box. Two buttons on the response box were dedicated to the response to the landing task: the right one to authorize landing, the left one to abort it. For each correct response, the score increased of 1 point. When participant missed a response, or made an incorrect response, this score did not increase. The score system was introduced to motivate the participants to perform the landing task. Two levels of visual/mental load were manipulated and equally likely to occur (see figure 1). For the low load condition, indicators appeared in green and no mental arithmetic had to be performed to deduce the rule to apply to the cursors positions.

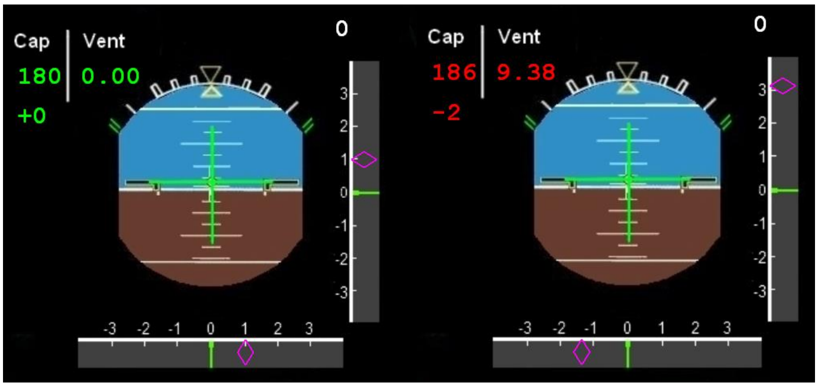

Figure 1. screenshots of a low load landing task video (on the left) and a high load landing task video (one the right). On the upper left corner is the heading to be added to the magnetic declination below. On the right is the wind. On the upper right corner is the current score to the landing task.

Indicators values	Condition on cursors to authorize landing
Nominal (= green, low load conditions)	Both cursors ∈ [-2; 2]²
wind and heading distant of less than 5 from their nominal values	Both cursors ∈ [-2; 2]²
wind or heading distant of more than 5 from their nominal values	One cursor ∈ [-1; 1], the other [-2; 2]
wind and heading distant of more than 5 from their nominal values	Both cursors ∈ [-1; 1]

Figure 2. Table of the rules for the landing task to analyse the cursors positions.

In high load conditions, the indicators appeared in red, the cursors were moving faster and mental arithmetic had to be performed to deduce the rule to apply to the cursors positions. To further increase the visual load involved by this task, a coloured circle was displayed during 150 milliseconds during each video, at a random time. This circled was either red (probability = 0.9) or green (probability = 0.1) and equally likely to be displayed on the right or on the left of the screen. A red circle was considered to be a visual alarm and had to be reported during the response window by pressing the central button on the response box. The circle was at least 500ms apart from the time the tone was played. The red circle could not be displayed when a deviant tone was played in the same trial, so that only one alarm top had to be reported per trial. For the oddball task they had to perform in addition to the landing task, during the 2 seconds response window, participants had also to press the central button of the response box if they heard a deviant tone. It reflected their ability to detect the auditory alarms (deviant tones) while performing a primary task. Percentage of correct response to the landing task and percentage of reported deviant tones were the dependant variables. The landing task was also displayed during the baseline oddball session, but participants only had to perform the oddball task. Participants were instructed that they should not pay attention to the landing task, reporting only the deviant tones.

Procedure

The whole procedure lasted 150 minutes, including 30 minutes to install and test the equipment and 60 minutes of EEG recording. After the behavioural tests, participants were all trained for the three experimental conditions during two sets of 20 trials for each, which contained all the possible situations they would encounter in the real experimentation. During this training, participants had to attest to the notification of both visual and auditory alarms, responding correctly to the alarm detection task at least once for each type of alarm. Then the EEG electrode cap, EOG and GSR electrodes were placed, prepared and tested. Participants seated then in a comfortable reclining armchair, placed in a dimly lit, sound-damped room. They were instructed to keep their forearms lying on the chair's arms, with their two hands resting on the response pad. The 400 experimental trials lasted 40 minutes. Participants then answered the NASA Task Load Index (NASA TLX) to give a detailed evaluation of their performance to the landing task and to the alarm detection task. Finally, participants had to go through the 200 baseline oddball trials (20 minutes).

Results

All statistical analyses were performed using IBM SPSS 20. Results were considered statistically significant when $p < .05$.

Performance measures

A t-test for paired samples indicated that the detection rate in the baseline oddball session did not differ in the low load condition (M = 96.67%, SD = 5.88%) and in the high load condition (M = 97.33, SD = 4.17%), $t(14) = .619$, $p = .546$. Therefore, both conditions were merged into one "control condition" for subsequent analyses.

Correct response rate to the landing task was assessed by a 2 x 2 ANOVA with within-subjects factors "load" (low or high) and "type of tone" (standard or deviant) in order to investigate the differences between conditions. The main goal of this analysis was to make sure there was truly a difference between the low load and the high load conditions and that participants followed instructions and accomplished the landing task as the primary task. If those assumptions were met, the performance would be higher in the low load condition than in the high load condition, and the type of tone would not affect performance. Results corroborated those two hypotheses. Correct response rate to the landing task in the low load condition (M = 96.7%, SE = 0.6%) was superior to the correct response rate in the high load condition (M = 90.2%, SE = 0.7%), $F(1, 14) = 91.596$, $p < .001$. There was no difference between trials with the standard tone (M = 93.2%, SD = 0.9%) and trials with the deviant tone (M = 93.8%, SD = 0.5%), $F(1, 14) = .385$, $p = .545$, and no interaction, $F(1,14) = .002$, $p = .968$.

Detection rate for the oddball task was examined. A t-test for paired samples showed that deviant tones were more detected in the low load condition (M = 80.17%, SD = 21.54%) than in the high load condition (M = 71.52%, SD = 26.67%), $t(14) = 2.385$, $p = .032$, as shown in figure 3.

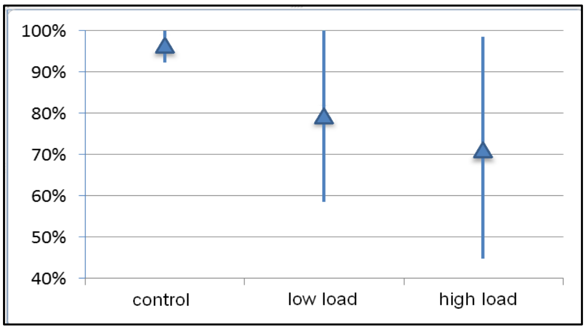

Figure 3: Detection rate of deviant tones depending on the perceptual and cognitive load of the primary task. "Control"represents the baseline oddball session.

ERPs measures

The P300 component was examined through a 3 x 3 x 2 ANOVA with within-subjects factors "electrode" (Fz, Cz or Pz), "load" (control, low or high), and "type of tone" (standard or deviant). Significant main effects were found for the electrode, $F(2, 28) = 17.068$, $p < .001$, the load $F(2, 28) = 17.810$, $p < .001$, and the type of tone, $F(1, 14) = 8.948$, $p = .01$. There were significant interactions between electrode and load, $F(4, 56) = 3.525$, $p = .012$, and between electrode and type of tone, $F(2, 28) = 16.261$, $p < .001$, but no other interaction was observed.

Simple main effects and multiple comparisons were further analysed using the LSD test. P300 were larger at the Pz (M = 5 µV, SE = .25 µV) than at the Fz (M = -1.1 µV, SE = .35 µV), $p < .001$, and the Cz (M = -.8 µV, SE = .35 µV), $p < .001$, recording sites, whilst Fz and Cz showed no difference, $p = .276$. The largest ERP was observed with the control condition (M = 1.55 µV, SE = .5 µV), followed by the low load condition (M = -.25 µV, SE = .55 µV), $p = .027$, and the high load condition (M = -2.7 µV, SE = .45 µV), $p < .001$, which also differed significantly, $p = .001$ (see figure 4). Finally, the deviant tone (M = .1 µV, SE = .4 µV) showed a higher P300 than the standard tone (M = -1.05 µV, SE = .25 µV), $p = .01$.

More specifically, for the three electrodes, the high load condition generated a lower P300 than the low load and the control conditions when the tone was standard, all $p < .01$, but there was no significant difference between the control condition and the low load condition on any of the recording sites. For the trials featuring a deviant tone, the pattern of results was the same, with the smallest P300 in the high load condition compared to both the low load and the control conditions, all $p < .01$. The Fz and Cz electrodes also showed no difference between the control and the low load conditions, but this difference appeared to be significant for the Pz electrode, the baseline oddball condition producing the highest P300, $p = .038$.

Again for the three recording sites, the difference between the standard and the deviant tones did not prove significant in both the low load and the high load conditions. In contrast, in the baseline oddball condition, the deviant tone generated a stronger P300 than the standard tone for the Cz and the Pz electrodes, respectively *p* < .05 and *p* < .001, whilst this difference did not appeared with the Fz electrode, *p* = .122.

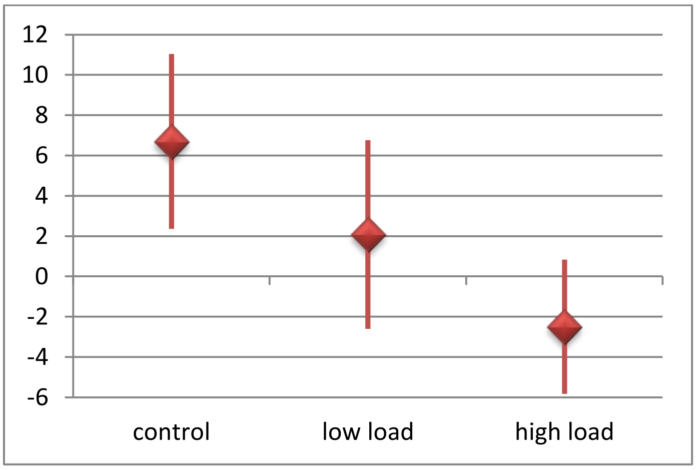

Figure 4: P300 mean amplitude and standard deviation in µVolts depending on the perceptual and cognitive load of the primary task, for target tones on Pz electrode. "Control"represents the baseline oddball session.

Discussion

Our study aimed at creating an experimental paradigm in which the inattentional deafness phenomenon could occur numerous times with each participant. We designed a simplified landing task with two levels of visual/mental load. While participants were subject to this task, an oddball paradigm was administered simultaneously to assess their ability to detect an alarm (*i.e.* the deviant sound in the oddball paradigm). We hypothesized that variations in visual/mental load will modify the ability of our participants to detect the alarm, generating inattentional deafness. In addition, we assumed that the diminution of the auditory P300 amplitude should be concomitant with the occurrence of inattentional deafness, and that this diminution of amplitude should be related to the visual/mental load level. The behavioural results showed that our task was successful in reproducing inattentional deafness. Whereas only 5% of alarms were missed during the baseline oddball session (oddball task only), 20% of alarms were missed when the oddball task was processed simultaneously with the landing task under low load condition, and this number increased to 30% under the high load condition. This is consistent with the results obtained by Macdonald and Lavie (2011) in which increased visual load was more likely to provoke inattentional deafness.

The effect of the introduction of visual/mental load on the ability to detect an alarm was significant in both behavioural results (number of sounds omitted) and electrophysiological measures, as showed by the variation in amplitude of the P300 component. Auditory P300 diminished in the landing task with low-load condition in comparison to the oddball baseline and further diminished with an increase of the load (high load vs. low load). These results confirmed that the primary task left few resources to treat auditory alarm in the low-load condition and even fewer in the high-load condition. It supports the hypothesis of a common pool of resources shared between visual and auditory modalities (Macdonald & Lavie, 2011). Variations in P300 amplitude also raise the question of short term memory effects on inattentional deafness occurrences and ERPS measurements. A difference due to memory (Dm) has been observed in ERPs measurements with memory paradigms (Friedman & Trott, 2000), in which participants study a list of materials and trials are sorted as a function of whether they go on to be remembered or not in a subsequent test phase. Such paradigms being very demanding on the short term memory, involving lists of several items to be remembered, and the test phase taking place separately and significantly after the study phase (several seconds to several minutes), we tried to avoid Dm effects by minimizing the amount of information to keep in mind in each trial and by reducing the duration during which information had to be remembered: no information had to be remembered for more than 4 seconds. Furthermore, the amount of information to manage was the same in each trial. Under such conditions, we prevented the most participants from simply forgetting they heard the alarm before having to report it, and short term memory was equally solicited in every trial so that no defference due to memory could affect participant's performance or measurements. We then assumed Dm was not significant in this experiment.

The major contribution of this study lies in the co-occurrence of inattentional deafness and ERP measurements. While inattentional deafness was studied through behavioural questionnaires following a single trial (Koreimann et al., 2009, Macdonald & Lavie, 2011), we developed a paradigm inducing multiple occurrences of inattentional deafness in a participant, rather than a single irreproducible occurrence in behavioural studies conducted so far (Macdonald, 2011). Another specific contribution of this work is the development of measurements of brain activity to electro-physiologically characterize the state of an operator suffering from inattentional deafness. EEG analysis showed that a drastic diminution of the auditory P300 amplitude was concomitant with the increased occurrence of inattentional deafness.

Conclusion

This study provides new behavioural and electrophysiological insights to explain the trend of pilots to ignore critical auditory information. We notably demonstrated that mental and perceptual workload interferes with concurrent appraisal of rare and unpredictable auditory alarms. P300 modulations supported this result and provide a more complete characterisation of the internal attentional mechanism responsible for observable behaviour. These results encourage the use of a neuroergonomic approach to study pilots' performance. This multidisciplinary approach, combining methods from neurosciences and human factors, is part of a commitment to improve aviation safety. Additional experiments with more participants and an EEG cap with 128 electrodes will be conducted to enable ERPs source localization and clarify the correlation between ERPs characteristics and the attentional state of a pilot in situations likely to provoke inattentional deafness. Further studies are also scheduled to establish the relevance of this approach to study new auditory alarm designs preventing inattentional deafness and to detect and predict in real time the deficiencies of pilots' attention. This study also opens the way to new paradigms using electrophysiological measurements on real pilots and co-pilots in a motion flight simulator.

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