Inattentional deafness to auditory alarms: Inter-individual differences, electrophysiological signature and single trial classification

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Abstract

Inattentional deafness can have deleterious consequences in complex real-life situations (e.g. healthcare, aviation) leading to miss critical auditory signals. Such failure of auditory attention is thought to rely on top-down biasing mechanisms at the central executive level. A complementary approach to account for this phenomenon is to consider the existence of visual dominance over hearing that could be implemented via direct visual-to-auditory pathways. To investigate this phenomenon, thirteen aircraft pilots, equipped with a 32-channel EEG system, faced a low and high workload scenarii along with an auditory oddball task in a motion flight simulator. Prior to the flying task, the pilots were screened to assess their working memory span and visual dominance susceptibility. The behavioral results disclosed that the volunteers missed 57.7% of the auditory alarms in the difficult condition. Among all evaluated capabilities, only the visual dominance index was predictive of the miss rate in the difficult scenario. These findings provide behavioral evidences that other early cross-modal competitive process than top down modulation process could account for inattentional deafness. The electrophysiological analyses showed that the miss over the hit alarms led to a significant amplitude reduction of early perceptual (N100) and late attentional (P3a and P3b) event-related potentials components. Eventually, we implemented an EEG-based processing pipeline to perform single-trial classification of inattentional deafness. The results indicate that this processing chain could be used in an

ecological setting as it led to 72.2% mean accuracy to discriminate missed from hit auditory alarms.

Introduction

Since the pioneering work of Cherry (1953) on dichotic listening, several studies have confirmed and expanded the findings that fully perceptible auditory stimuli can remain undetected under perceptual and attentional demanding settings. Echoing elegantly with the famous inattentional blindness paradigm of Simons and Levins (1997), Dalton and Fraenkel (2012) have shown that participants might experience inattentional deafness by failing to notice the sentence “I am a Gorilla” while attending to an auditory conversation. The occurrence of this phenomenon has also been demonstrated in music listening, whereby some listeners were unable to report a salient electric guitar solo embedded in the XIXth century “Thus Spoke Zarathustra” lyrics poem (Koreimann et al., 2014). Cross-modality interactions are also known to induce inattentional deafness and drive some relevant research on this topic. Accordingly, there is now a solid corpus of evidence that the detection of auditory cues may be impaired when engaged under visually demanding settings (Lavie et al., 2014; Macdonald & Lavie, 2011; Raveh & Lavie, 2015; Scheer et al., 2018).

These studies provide valuable explanations to conceptualize attentional failures to auditory alarms that have been reported in complex real-life situations (Hasanain et al., 2017). This is particularly true in aviation whereby safety analyses have reported absence of response to auditory alarms as a causing factor to several accidents (Bliss, 2003; Mumaw, 2017). For instance, the co-pilot of the ill-fated Air France flight 447 from Rio de Janeiro continued to put the aircraft into a steep climb instead of descending, despite more than 70 audible stall warnings (Bureau d’Enquêtes et d’Analyses, 2012). Some experiments conducted in realistic flight simulators (Dehais et al., 2012; Dehais et al., 2010; Dehais et al., 2014) and in actual flight conditions (Dehais et al., 2017) confirmed that inattentional deafness could indeed occur in the cockpit at an early perceptual (Callan et al, 2018; Durantin et al., 2017) or at a later attentional stage (Giraudet et al., 2015).

It is generally admitted that the existence of limited cognitive resources at a central level may account for transient attentional impairments (Brand-D'Abrescia & Lavie, 2008; Santangelo et al., 2007; Hannon & Richards, 2010; Tombu et al., 2011) such as inattentional deafness (Raveh & Lavie, 2015). Accordingly, individuals with a higher pool of central resources – as measured by working memory span – tend to exhibit better divided and sustained attentional abilities (Colflesh & Conway, 2007; Unsworth & Engle, 2007) and should be more likely to detect unexpected events during highly demanding tasks. However, the authors reported an absence of correlation between individual working memory capacity and inattentional deafness (Kreitz et al., 2016b). The latter concluded that their results appealed in favor of the attentional set theory (Most et al. , 2005) which stipulates that only task relevant stimuli are attended to and consequently processed. One could envisage the implementation of shielding mechanisms controlled at a central level to save the future efforts required to perform the task at hand and hence avoid resource depletion (Tombu, et al, 2011; Fritz Elhilali, David, et Shamma, 2007). These mechanisms described by Hancock and Warm (1989) and Hockey (1997), may lead one to think that the brain enters a "fail-safe mode", limiting the access to the pool of resources to process unexpected signals such as auditory ones.

A complementary hypothesis that has not yet been considered to account for inattentional deafness could be linked to the existence of visual dominance over hearing mechanisms (Colavita & Weisberg, 1979; Sinnett et al., 2007; Yuval-Greenberg & Deouell, 2009). Accordingly, a recent experiment reported a superior ability to inhibit irrelevant spatial auditory distractors when processing visual targets than the opposite (Scannella, et al., 2016). The authors argued that the existence of direct visuo-auditory pathways (Cappe & Barone, 2005; Macaluso & Driver, 2005; Wang et al., 2008) could underpin the modulation of auditory processing. Since flying mainly involves the processing of visual cues (e.g. gauges, out of the window environment), it is more likely that pilots are biased to rely on these latter than on auditory ones when facing critical situations (Scannella et al., 2013). To the authors' best knowledge, no study has yet attempted to validate the hypothesis of such interactions between visual and auditory modalities, especially in ecological settings.

Beyond the understanding of the mechanisms underpinning inattentional deafness, there is a need to implement online mental state monitoring based on neurophysiological measures to detect the occurrence of this phenomenon. Tremendous progress has been achieved using cerebral measures to infer cognitive state using processing pipelines called passive brain-computer interfaces (pBCIs; Zander & Kothe, 2011). In laboratory settings, EEG-based passive BCIs have enabled researchers to accurately estimate various mental states of interest for transportation applications, such as mental fatigue and cognitive workload (Roy et al., 2016a; Hsu & Jung, 2017). Previous research indicated in particular that this approach successfully led to classify auditory processing at the single trial level in an oddball paradigm (e.g. frequent *versus* rare sounds; Debener et al., 2015) and in an absent *versus* present auditory sound paradigm under flight simulator and real flight settings (Callan et al., 2015).

In the present paper, we report the results from a study dedicated to 1) assess the visual dominance over hearing hypothesis as a predictor of failure of auditory attention, 2) to identify electrophysiological correlates of inattentional deafness and 3) to implement a passive BCI to detect alarm misperception. To meet these goals, the volunteers were asked for their flight experience (number of flying hours) and screened with two cognitive tests dedicated to assess their working memory span and their visual dominance over hearing index respectively. Pilots were then placed in a motion flight simulator and faced low and a high workload flying scenarii while responding to rare auditory targets (Oddball paradigm). In the low workload scenario, the participants had to supervise the flight trajectory controlled by the auto-flight system. In the high workload scenario, they had to perform a critical landing with no visibility and smoke in the cabin to simulate a fire. An expert pilot, silently observing the participants, was also left seated in the simulator as an additional stressor. We hypothesized that the difficult scenario, combining high visual task demand and psychological stress, would affect both early and late auditory processing to an extent that it would yield to a high auditory alarm miss rate. This latter point was of importance so as to conduct electrophysiological-based sound detection analyses and to train a classifier to detect inattentional deafness.

Material and Method

Participants

Thirteen healthy male pilots (mean age = 26.3 years, SD = 5.2; flight experience = 81.1 hours, SD = 43.8), all French defense staff from Institut Supérieur de l'Aéronautique et de l'Espace (ISAE-SUPAERO) campus, were recruited by local advertisement and did not receive any payment for their participation. They all reported normal or corrected-to-normal vision and normal audition. Typical total duration of a subject's session (informed consent approval, practice task, and real task) was about two hours and a half. This work was approved by the Inserm Committee of Ethics Evaluation (Comité d'Evaluation Ethique de l'Inserm—IRB00003888 - 18-460).

Working memory and visual dominance assessment

The subjects were asked to perform two neuropsychological tests. These tests consisted of a working memory test (N-back task), and a spatial audiovisual conflict test to derive a visual over hearing dominance index.

N-back task: This test has been applied using the neuropsychological testing battery PEBL® (Mueller & Piper, 2014). The stimuli were presented on a computer screen, and consisted in the appearance of successive letters every 3 seconds in the center of the screen along with the same letter pronounced in a headphone (see Figure 1). The participants had to press the left "Shift" key when the current letter was identical to the N-2 one (2-back). The subject then had to repeat the experiment with no more letters, but a square moving in a 3 * 3 square grid. When the square appeared twice in the same box, the subject had to press the right "Shift" key.

Figure 1 about here

Spatial audiovisual conflict task: The task design was adapted from Scannella and collaborators (2015). Stimuli were delivered with Presentation software (Neurobehavioral system). Auditory stimuli (i.e. 1000 Hz normalized pure tones at 78 dB SPL) were presented using binaural headphones and visual stimuli (i.e. filled white circles of 2-degree diameter), were presented at a constant angle of 15 degrees on the left or the right of a white central fixation cross on a MSI 17" monitor placed one meter in front of the participant. Auditory and visual stimuli were presented simultaneously during 200 ms and were either on the same side (i.e. congruent trials), or on opposite sides (i.e. incongruent trials; Figure 2). The inter-trial interval was set to 2100 ms with a 500-ms jitter, while the white fixation cross remained always visible. Behavioral responses (accuracy and reaction times) were recorded with a 2-button mouse (left button for left target; right button for right target) across two blocks. In one block, participants had to detect the presentation side of the visual stimuli while ignoring auditory distractors; in the other block, they had to detect the auditory stimuli while ignoring visual distractors. In both blocks, they had to focus on the central fixation cross. The presentation order of the two blocks was counterbalanced across participants. For each block, 60 congruent and 60 incongruent trials were presented resulting in two 5-minute blocks.

Figure 2 about here

Flight simulator

The ISAE three-axis motion (roll, pitch, and height) flight simulator designed by the French Flight Test Center was used to conduct the experiment (Figure 3). It simulates a twin-engine aircraft flight model and the user interface is composed of a Primary Flight Display, a Navigation Display, and an upper Electronic Central Aircraft Monitoring Display page. The flight simulator is equipped with classical actuators such as the sidestick, the rudder, the throttle, the flaps levers and a complete autopilot to control the flight. Two stereophonic speakers, located under the displays on each side of the cabin, were used to broadcast continuous radio communications, engine sounds (77 dB SPL), and to trigger the oddball sounds (90 dB SPL).

Figure 3 about here

Flying scenarii

The participants performed one low and one high workload scenarii along with a classical oddball paradigm with a total of 400 auditory stimuli: 20% were targets (i.e. 80 sounds) and 80% were non-targets (i.e. 320 sounds). Two types of sounds were used: one pure tone at 1000 Hz and one pure tone at 1100 Hz, both normalized at 90 dB SPL. Half of the volunteers had the 1000 Hz tone as a target and the 1100 Hz tone as a distractor whereas the other half had the opposite. Stimuli were presented through the simulator sound system at a random time interval of 2 to 5 s (mean = 3.5 s) resulting in a total of two 24-minute sessions. The volunteers had to ignore the frequent non-targets and used the trigger of the side-stick to respond to the auditory targets only. The order of the two scenarii was counterbalanced across participants. The participants were expressly asked not to prioritize on a specific task (flying or responding to alarms) and that their performance level was calculated based on both their flying accuracy and hit rate. A former air force pilot was right seated during the two flying conditions. He did not perform any actions and was silently observing the participants. These latter were told that this expert pilot's judgement was used to evaluate their behavior and performance. The presence of the expert pilot was used as an additional stressor to induce social pressure (Shrauger, 1972). Indeed, the feeling of being observed and evaluated by one's peers is known to increase anxiety (Frisch et al., 2015; Allen et al., 2014) that in return negatively affect attentional control (Allsop and Gray, 2014). It was expected that this deleterious effect on attentional abilities would be magnified in the high workload scenario and contribute to induce inattentional deafness.

Low workload scenario: This scenario was the reference flight. In this experimental condition, the autopilot was engaged to level off the plane at a constant speed. The only task for the pilot was to respond to the auditory target stimuli while supervising the flight trajectory.

High workload scenario: The pilot had to perform a night approach and landing on the runway 14R at Toulouse Blagnac airport (France) while facing a cabin fire that was simulated using a Power Lighting Fogburst 600 W generator and a flashing red light. The aircraft position was initialized 20 nautical miles (nm) from the airport at an altitude of 4000 feet, a heading of 310 ° and a speed of 170 knots (kts). The volunteers had to steer 200° while descending to an altitude of 3000 feet. When reaching a 12-nm distance from the airport, participants had to turn to the west (heading 270°) until they intercepted the runway axis using the instrument landing system. Once intercepted, the pilots had to take a heading of 144° in order to line up with the center line of the runway. At 5 nm from the landing ground, they had to reduce speed to 130 knots to initiate the final descent. The presence of an airplane on the runway required the pilots to perform a go around and to circle around at an altitude of 2500 feet to realign on the runway axis and try to land again. The visibility was bad, causing the airport to appear and disappear several times between the cloud layers.

Protocol

Once the participants were told about the purpose of the experiment and signed the informed consent, they first started to complete the two cognitive tasks (N-back task and Spatial audiovisual conflict task). The order of these two cognitive tasks was counterbalanced across participants. The volunteers were then introduced to the flight instructor who trained them for a 30-minute session to handle the simulator and to perform several manual approaches and landings. The participants were also trained to perform the oddball task for 5 minutes. After the training was completed, the EEG and the ECG electrodes were respectively placed on the volunteers' head and torso. The experiment was eventually started: the simulator motion was engaged to reproduce realistic flight sensations, and a continuous radio communication was also broadcasted to reproduce more ecological flight conditions. The participants had to fly the two scenarii in a random order under the silent supervision of the flight instructor.

Data acquisition and processing

EEG data were recorded continuously with the BioSemi ActiveTwo EEG system (BioSemi, Amsterdam) from 32 active Ag-AgCl scalp electrodes positioned according to the International 10/20 system, at a 512 Hz sampling rate and with a 0–104 Hz band-pass filter. During the experiment, electrode offsets were kept under 20 mV as recommended by the manufacturer. The data were then re-referenced offline to the algebraic average of the left and right mastoids, down-sampled to 500 Hz, and filtered with a band-pass FIR filter of 0.1–40 Hz. An independent component analysis was performed using the RUNICA function with EEGlab (13.4.4b version) to isolate and reject eye blinks and movements. Data were later segmented into 1200 ms epochs starting 200 ms before the onset of each sound. Then, ERPs were computed with a baseline correction using the first 200 ms (i.e. pre-stimulus activity).

Two external EEG channels were additionally used to measure the heart rate (EX7 placed on the left clavicle and EX8 placed on the left ribs of the participants). The R-R intervals of the raw ECG signal were then detected using the build-in QRS detection algorithm of Kubios HRV software (Tarvainen et al., 2014). All the recordings were manually revised for missed or false positive R peak detections. We eventually computed the average Heart Rate (HR, in beat per minute) for each scenario and participant.

Analyses

Electrophysiological statistical analyses were carried out using the built-in EEGlab permutation test. P-values were adjusted using the false discovery rate (FDR) corrections. All other statistical analyses were carried out using Statistica (V10, StatSoft). The p-value threshold for significance has been set to 0.05 if not otherwise mentioned. When appropriate, post-hoc comparisons have been carried out using the Tukey's Honestly Significant Difference test. Correlational analyses were conducted using Pearson correlation test.

Flight Performance: Participants' ability to succeed in landing the airplane was used as a binary performance index. Indeed, the scenario was designed in such a way that any deviation from the flightpath would lead the pilots not to reach the runway threshold on time.

Visual dominance index (Vdi): This index was meant to represent the propensity to be less distracted by auditory information when paying attention to visual ones than the opposite (Scannella et al., 2016). It has been calculated as the reaction time cost difference between the time to detect an auditory target (A_{inc}) and the time to detect a visual target (V_{inc}) in audiovisual incongruent trials: $Vdi = A_{inc} – V_{inc.}$

N-back accuracy: N-Back accuracy scores were averaged for each subject within each difficulty level.

Oddball accuracy: A two-tailed t-test was carried out on the number of missed auditory targets between the low and high workload scenarii to evaluate the impact of scenario difficulty on the detection rate of auditory alarms.

Auditory miss rate correlations: A linear multiple regression analysis with the flight experience, the visual dominance index and the working memory score within the high load scenario was conducted to find out which of the flying experience, the visual dominance susceptibility or the working memory ability was the most predictive of the auditory alarm miss rate.

ECG: To evaluate the impact of scenario difficulty over the heart rate as computed from the ECG signal, a two-tailed t-test was carried out on the whole flying scenario between the low and high workload scenarii.

Group ERP analyses: Point-by-point permutation tests from EEGLAB (v13.4.4b) were used to analyze Hit (i.e. correctly detected target) *versus* Miss (i.e. undetected target) ERP component amplitudes for all 32 electrodes.

ERP Classification analyses: A classification analysis was performed in order to determine whether alarm misperception could be detected in a reliable fashion. The main idea is to train a learning algorithm on a portion of the data and then test it on the remaining data. Here we focused our work on a single-trial classification, i.e. estimating from one single ERP whether the alarm is missed or detected by the pilot. The processing chain – that is to say the various algorithm parts- used to perform hit *versus* miss estimation was based on the ERPs of the target sounds and is described hereafter. Initially, the first 500 ms of the auditory ERPs were corrected for ocular artifacts in an automated fashion using the SOBI algorithm (Second Order Blind Identification) and the vertical EOG (Electrooculographic) signal. The two sources that were most correlated with the EOG activity were cancelled out. Next, the cleaned data were decimated to 100 Hz and centered on zero. Then, they were spatially filtered using a Canonical Correlation Analysis (CCA) filtering process that is shown to increase discriminability for ERP-based BCIs (Roy et al., 2015; Roy et al, 2016). Two CCA filters were used. Hence the features consisted of a vector of 100 points (2 filters*50 ERP time points). Lastly, these features were classified using a Fisher Linear Discriminant Analysis with a shrinkage estimation of the covariance matrices (Blankertz et al., 2011). This was performed using a 10-fold cross-validation procedure in which an equal number of hits and misses were systematically drawn to create the training (9 out of 10 subsets) and the testing sets (10^{th} subset).

Results

Behavioral and physiological results

Scenario effect: We found that the target sound detection accuracy was significantly affected by the scenario load with only 0.33 % (± 0.47) of missed targets in the low load scenario compared to 57.73% (±12.63) in the high load one ($t=15.73$, $p<0.001$, Cohen's $d=-6.44$) (Figure 4).

Figure 4 about here

Flying performance: All the pilots managed to land the aircraft on the runway prior to the end of the experiment.

Linear regression analysis: Among the three auditory miss predictors that were tested (Figure 5), the visual dominance index was the only one that significantly correlated with the percentage of missed auditory targets during the high load scenario (semi-partial r=0.57; t=2.60; p<0.05). This correlation showed that the more the pilots can be distracted by the visual distractor while responding to the auditory target in the audiovisual conflict task, the higher the number of missed auditory alarms in the high load flying scenario. The working memory ability and the flying experience correlated only poorly and non-significantly with the number of missed auditory targets (semi-partial r=-0.16; t=1.48; p=0.47 and semi-partial r=-0.32; t=0.75; p=0.17 respectively).

Figure 5 about here

ECG results: The statistical analyses disclosed a significant effect of the scenario difficulty over the cardiac activity t=2.68; p<0.05, Cohen's d=1.06) with a higher average HR in the high workload scenario (mean= 89.5, SD= 17.2) than in the low workload one (mean = 72.8, SD= 14.3).

Electrophysiological results

In the high load flying scenario, both auditory targets and distractors have elicited event related potentials with different components. Among them we found characteristic auditory-related exogenous (N100/P200) and endogenous (P3a and P3b) components (see Figure 6). The N100 reached its maximum mean amplitude around 116 ms with a fronto-central scalp distribution. The mean hit-related N100 amplitude was significantly larger than the miss-related one (hit: -7.92 µV, miss: -5.49 µV; $p<0.05$, Cohen's d=0.65). Similarly, the P3a component, with a centro-parietal distribution was maximum at 370 ms for the hit auditory targets and larger than the miss-related ones (hit: 2.48 µV, miss: 0.65 µV; $p<0.05$, Cohen's d=0.62). Finally, the P3b component amplitude was also affected by the detection type and led to a maximum amplitude 450 ms after the stimulus onset in the parieto-occipital region. Its amplitude was significantly larger for the detected sounds (2.99 µV) than for the missed ones (-0.25 µV; $p<0.001$, Cohen's d=1.28).

Figure 6 about here

Single trial inattentional deafness classification: The classification pipeline that was used allowed us to obtain 72.2% of correct classification of the hit and missed targets in average across participants. This is significantly higher than the adjusted chance level threshold of 59%, as computed to take into account the number of available trials following Combrisson and Jerbi's recommendations (2015). Figure 7 displays the spatial patterns of the filters used to enhance the discriminability between the two classes (i.e. hit and miss). As mainly illustrated by the first filter's patterns, the electrode sites that enable such a high classification accuracy are located at fronto-central sites.

Figure 7 about here

Discussions

The objective of this paper was to study the inattentional deafness phenomenon under ecological settings in the context of flying. A first research question was to identify individual specificities that could reveal evidences of visual to auditory dominance as a possible complementary mechanism to account for inattentional deafness. A second research question was to identify the electrophysiological correlates of inattentional deafness to auditory alarm in the cockpit. Eventually, a last question was to assess the reliability of an off-line processing pipeline dedicated to detect alarm misperception using electrophysiological responses.

To meet this goal, the participants had to face two contrasted flying scenarii in terms of difficulty while responding to auditory alarms. The high workload scenario combined several stressors such as high cognitive demand (landing with no visibility and windshear), aversive stimuli (smoke in the cabin and flashing red light) and social pressure with the presence of an expert pilot. Accordingly, psychophysiological results disclosed that the HR was higher during the high workload scenario compared to the low workload one hence reflecting increased mental demand and psychological stress (Dehais et al., 2012; Dehais et al. , 2011). The behavioral results showed the efficiency of the high workload scenario to promote high rates of auditory misses (i.e. 57%) in comparison to the low workload one. These findings confirmed that primary task difficulty (Durantin et al., 2017; Giraudet et al., 2015; Macdonald & Lavie, 2011; Molloy et al., 2015) as well as unexpected stressful situations (Dehais et al., 2014) can elicit inattentional deafness in the cockpit. Our experimental protocol can't allow us to conclude which of the stressors was the most efficient to distract the pilots from processing the auditory alarms. Indeed, as we did not manipulate them separately, it is more likely that the combination of all these stressors had the intended deleterious effects on auditory attentional abilities (Allsop & Gray, 2014).

This high rate of inattentional deafness allowed however to conduct correlational analyses. The objective was to determine whether individual working memory, flying experience or visual dominance index would predict occurrence of inattentional deafness. As hypothesized, the working memory score did not predict the propensity to remain aware of the auditory alarms. This result is in line with previous studies that report an absence of relation between the working memory span and the occurrence of inattentional blindness (Beanland & Chan, 2016; Bredemeier & Simons, 2012; Kreitz et al., 2016a; Kreitzet al., 2016b) or inattentional deafness (Kreitzet al., 2016b). Though working memory capacity—as a measure of cognitive resources at a central – level—has been shown to be related to individuals' sustained and divided attentional performance (Colflesh & Conway, 2007; Sörqvist et al., 2012; Unsworth & Engle, 2007), this construct seems not appropriated to account for inattentional deafness. In line with Kreiz and collaborators (2016b), our results rather advocate in favor of the attentional set theory (Most et al., 2005): cognition is goal-directed and promotes the selection and the processing of task at hand relevant stimuli. In our experiment, the participants were told that the two tasks (i.e. flying and responding to auditory alarms) were of equal importance but the behavioral results suggested that the volunteers probably prioritized the flying task as they all managed to land the aircraft while missing at least 20% of auditory alerts in the best case. Pilots are highly trained individuals who are taught to prioritize tasks according to the "first aviate, then navigate and eventually communicate" rule. The application of this rule can explain why our volunteers may have naturally put more mental efforts on the flying task. The flying task was naturally more challenging and rewarding from a pilot's perspective (i.e. night landing with smoke in the cabin with an experienced flight instructor on the right seat) and had immediate consequences (i.e. missing the approach and the landing) contrary to the achievement of the auditory alarm task itself. Consequently, and in accordance with the attentional set theory, the participants were more likely to process visual information in the cockpit and were less inclined to respond to auditory targets. Such behavior well as the absence of correlation between inattentional deafness rate and working memory abilities could be predicted by the Compensatory Control Model (Hockey, 1997). This model postulates the existence of a motivational control mechanism that dynamically modulates mental effort to shield against performance decline and resources depletion. It includes three decisions units that are dedicated to select and hierarchize goals according to their utility value (the goal regulation unit), to monitor the efficiency of the on-going strategy (performance evaluation unit) and to increase or maintain mental effort (effort regulation unit). The effort regulation unit involves a compensatory allocation of resources, eventually leading to increased level of effort budget to maintain high utility goals that are compromised to the detriment of low priority ones. Indeed, goals with high utility, such as operating the aircraft in our task, would remain in place but with a higher level of mental effort to process visual flight parameters. Thus, one has to consider that such resources allocation is a dynamic process that could not depend on a structural characteristic such as working memory.

Eventually, and in line with our hypothesis, visual dominance over hearing mechanisms could provide complementary explanations to account for this phenomenon. Indeed, the ability to respond to auditory targets was biased by inter-individual cross-modality susceptibility: the "more visual dominant" volunteers exhibited a higher miss rate than the "less visual dominant" ones in the difficult scenario. These early mechanisms could possibly be implemented via direct visual-to-auditory connections (Cappe & Barone, 2005; Macaluso & Driver, 2005; Wang et al., 2008) to modulate the auditory response at the brainstem (Sörqvist et al., 2012), the auditory cortex (Scannella et al., 2013; Scannella et al., 2016) and/or the auditory integrative levels (Molloy et al., 2015). The strength and the efficiency of these visuo-auditory interactions may vary among individuals according to their modality preferences that are known to impact their abilities to process auditory or visual materials (Besson & Faïta, 1995; Besson et al., 1994; Cecere et al., 2015; Gurler et al., 2015; Jensen, 1971).

A second motivation of this study was to identify the electrophysiological correlates of auditory alarm misperception. The high miss rate in the difficult scenario allowed performing a miss versus hit contrast. In line with Callan and collaborators (2018), our findings disclose that the N100 amplitude was significantly reduced for misses compared to hits. This result shows that inattentional deafness to auditory alarms can take place at an early perceptual stage or processing as this component is the electrophysiological signature of stimulus detection and processing in the primary auditory cortices (Hink et al., 1977). This is also consistent with a previous inattentional deafness fMRI study, using a repetitive single tone auditory stimulus, that disclosed lower auditory cortex activation during auditory misses in comparison to auditory hits (Durantin et al., 2017). We found, in addition, that he processing of the auditory alarms was also consequently affected at later attentional stages during inattentional deafness events. Indeed, the amplitude of two subcomponents of the P300, namely the P3a and the P3b, were significantly diminished for misses relative to hits. On the one hand, the P3a, also known as early novelty P3, is thought to reflect automatic orientation and engagement of attention towards unexpected stimuli (Polich, 2007). On the other hand, the P3b, also known as late novelty P3, has been proposed to account for stimulus recognition involving working memory mechanisms (pattern matching and updating) (Kok, 2001; Polich, 2007). This is akin to previous inattentional deafness findings reporting lower auditory-related P300 (Giraudet et al., 2015), P3a (Molloy et al., 2015) and P3b (Scheer et al., 2018) amplitudes associated with the impaired processing of deviant sounds while performing a demanding visual task. However, these authors did not perform hit versus miss contrast as the miss rate was too low in their studies and thus solely reported the deleterious effect of visual load on the global (i.e. hits and misses averaged) auditory-related P300, P3a and P3b. We hence confirm previous results and reconcile the literature by showing that both early and late auditory processing stages are affected during inattentional deafness events. In accordance with other authors (Callan et al, 2018; Durantin et al, 2017), our assumption is that inattentional deafness is related to the lack of detection of the warning taking place at the early perceptual level (as attested by the N100 effects). Hence, subsequent processing at later attentional stages could be affected by this early effect (i.e. P3a and P3b attenuation). The attenuation of the P3a and P3b amplitudes also reveal that inattentional deafness could result from an inability to automatically shift attention to the alarm that has been correctly detected or from an inability to process and recognize the warning.

Eventually, our last motivation was to perform classification of EEG features that reflect the auditory alarm misperception. To that end, we implemented a signal processing chain that had proven its efficiency for auditory evoked-potentials classification (Roy et al., 2015; Roy et al., 2016). Thanks to this chain, we achieved a satisfying accuracy of 72.2% of correctly classified hit *versus* missed targets, a significantly higher accuracy than the adjusted chance level (i.e., 59%). These results indicate that this chain could be used in a quite ecological setting (i.e. a full motion flight simulator) to detect the inattentional deafness phenomenon.

Mental state estimation is a growing research interest and although high performance is reached nowadays in the laboratories, studies remain to be carried out to determine solutions for ecological settings. To our knowledge, this study is the first demonstration that inattentional deafness could be estimated in such settings. The natural next step is to achieve an online estimation, i.e. to estimate the operator's mental state and potential misperception of alarms during the realization of the task. Moreover, efforts should be spent to try and perform this estimation as early as possible, that is to say using data that precedes the occurrence of a stimulation (e.g. one minute or one second before the alarm is triggered), as currently studied by Senoussi and collaborators (2017). In this case we would predict rather than detect the occurrence of inattentional deafness. As a consequence, one could imagine the design of an adaptive cockpit that would take the information of stress level and inattention to alarms into account to implicitly adapt itself with a set of counter-measures (Glatz et al, 2018).

Conclusion and limitation of this study

This study demonstrates the importance of conducting neuroergonomics experiments in ecological settings rather than in simplified laboratory settings. This approach contributes to the understanding of the brain when facing critical real-life situations (Callan et al., 2018; Dehais et al., 2017; Gateau et al. 2018; Gramann et al. 2017; McKendrick et al. 2015) and allowed us to obtain high miss rates that could not be induced in laboratory conditions. In addition, our study is the first to report a relationship between individuals' visual dominance over hearing susceptibility and failure of attention. This result opens promising perspectives for human operator selection and the development of cognitive training solutions to improve auditory abilities. Taken together, the behavioral and electrophysiological results of this experiment bring insights on subtle competitive mechanisms taking place from the perceptual to the later attentional stages. This study thus brings clues that conciliate diverging studies attributing the inattentional deafness phenomenon to pre-attentive (Callan et al., 2018; Scannella et al., 2013) or attentional processes (Causse et al., 2016; Giraudet et al., 2015; Scheer et al., 2018). Eventually, the finding of ERPs as a neural signature of inattentional deafness shows that they are good candidates as features to detect the occurrence of missed alarms using passive brain-computer interfaces and could be used to design adaptive "alarms" (e.g. dynamic modification of the alarm modality) and feedback to mitigate transient attentional impairments.

This study was a first step toward the identification of potential behavioral and neural correlates of inattentional deafness and the implementation of a pBCI. To meet this goal, the design of our protocol relied on a compromised between ecological and controlled laboratory settings. This approach has several limitations though. For instance, the participants faced a high number of auditory targets, contrarily to real operational situations. The high rate of these auditory alarms was needed for our ERP analyses and machine learning purposes. The alarm sound was also not a real cockpit alarm but a brief and pure tone to be consistent with classical auditory oddball paradigm so as to elicit typical ERPs in a timely manner. Moreover, these alarms were not related to the flying task per se: missing the alarms had no consequences on the flight performance although it was mentioned that the global flight appreciation would take the alarm hit rate into account. As a matter of face, these frequent and "non-relevant" alarms were more likely to be ignored by the participants. Eventually, our flight simulator did not allow collecting flight parameters. This prevented us from analyzing possible shared attentional strategies between the flying and the auditory alarm detection tasks throughout the flight. Further experiments should integrate more realistic alarms relevant to the flying task and the analysis of the flight performance that could also be used to improve the classification algorithm to predict inattentional deafness. Finally, other experiments should investigate the effect of time-on-task on inattentional deafness as previous studies have shown that it can negatively impair auditory processing (Dehais et al. 2018).

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Figure Legends

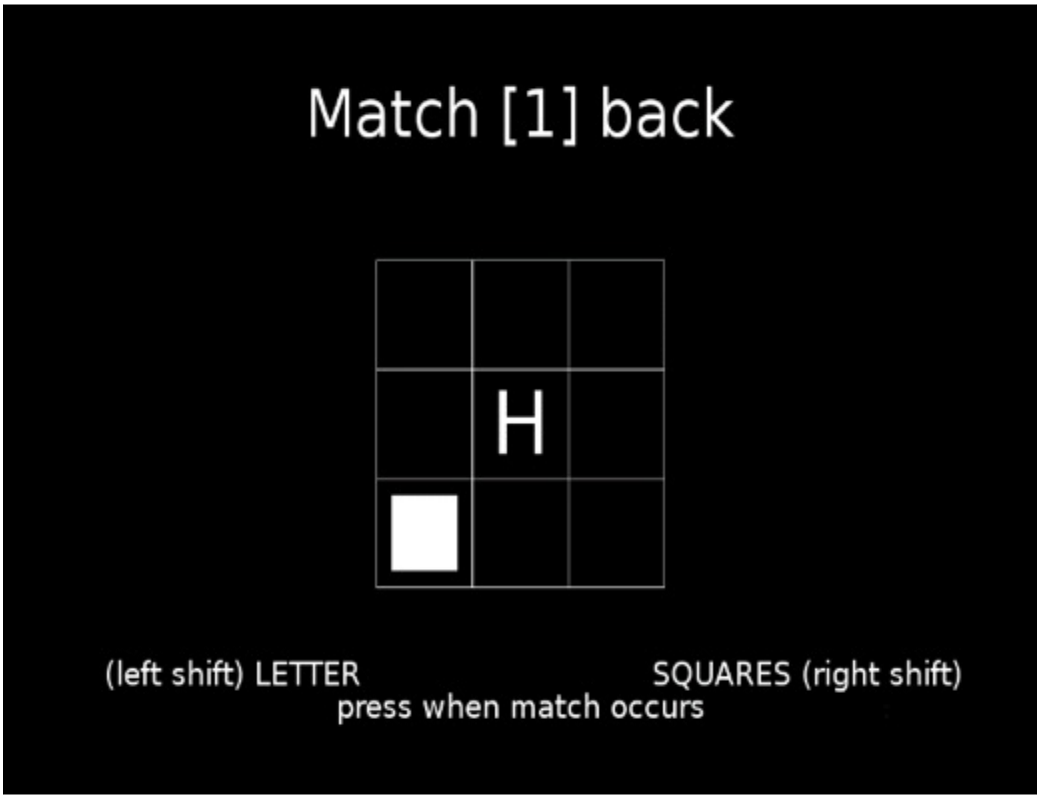

Figure 1. The N-back task – stimuli were either letters displayed in the center of the 3*3 grid or a moving square. Here the condition is "N-1" back.

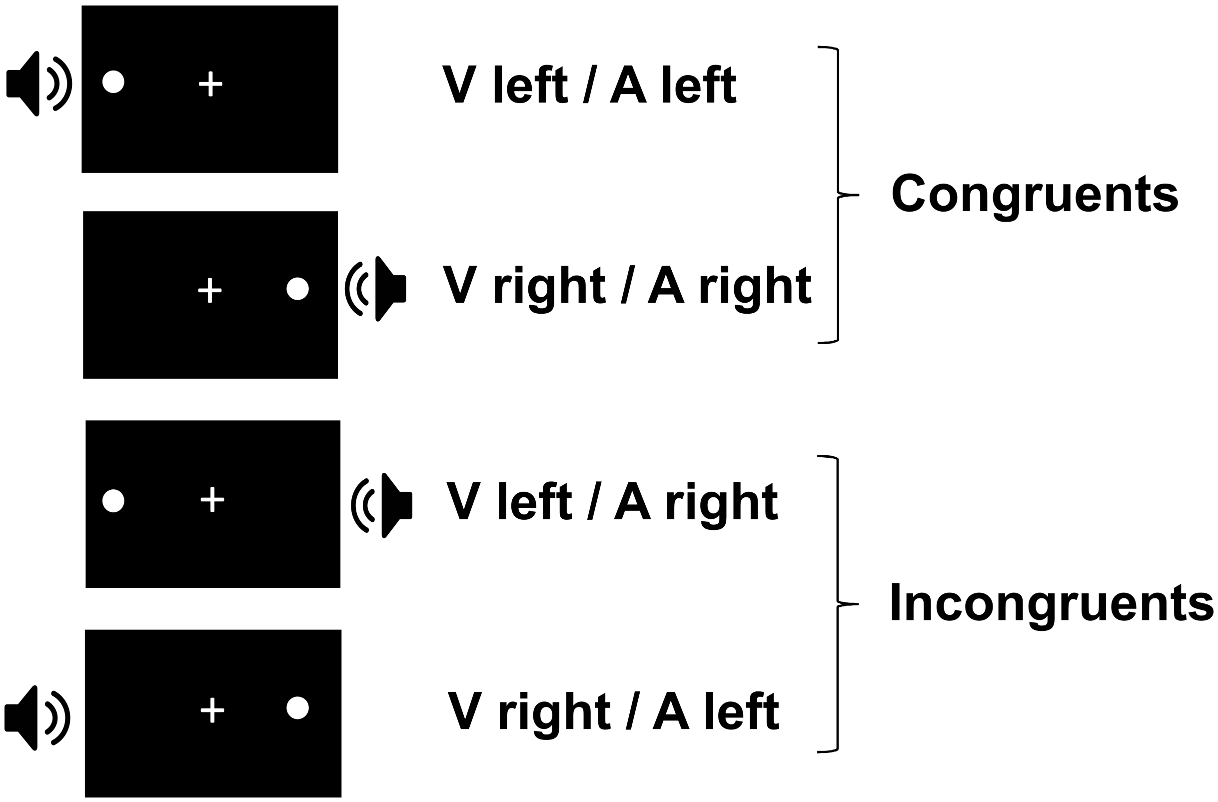

Figure 2. Spatial audiovisual conflict task. Stimuli (sounds and white circles) were presented either on the same side (congruent trials) or on opposite sides (incongruent trials).

Figure 3. ISAE-SUPAERO three axis motion flight simulator. The participants were left seated and equipped with a Biosemi 32-electrode EEG system.

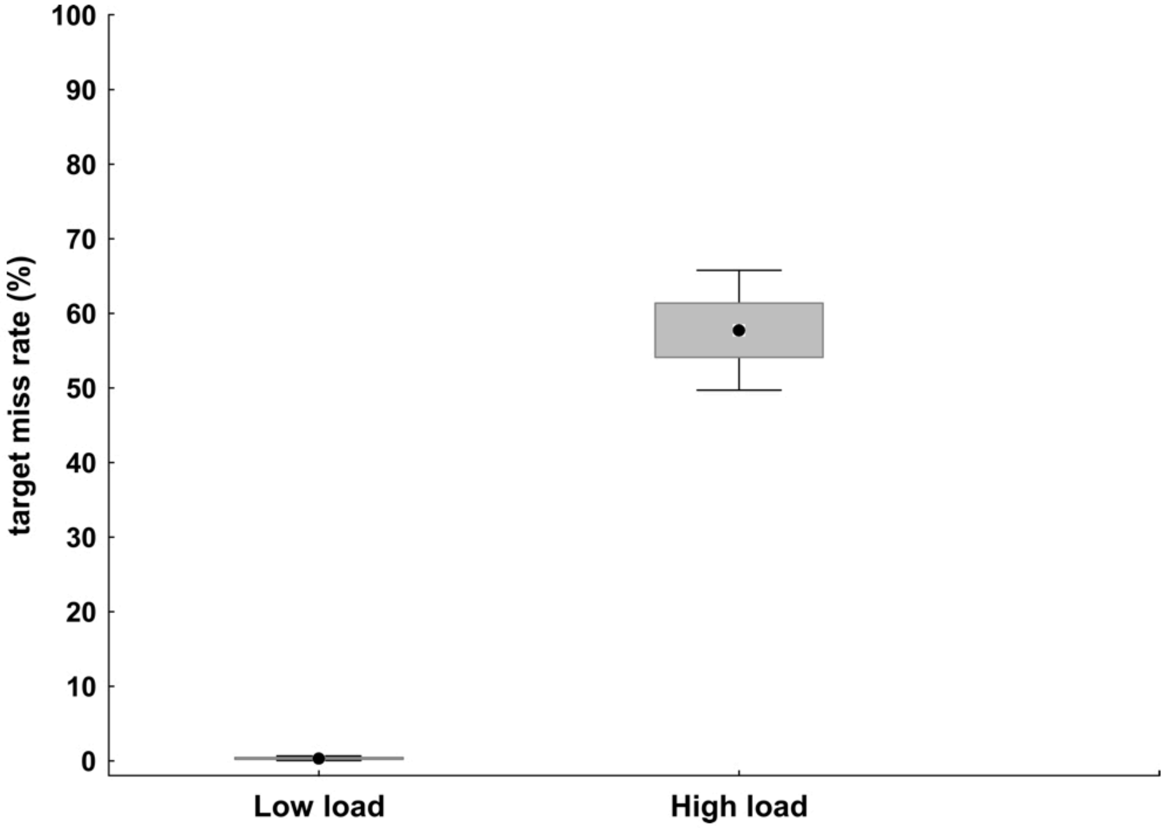

Figure 4. Scenario effect over the oddball auditory target detection. The dots represent the mean accuracy over the group, the grey box and the whiskers respectively represent the standard deviation and the 95% confidence interval.

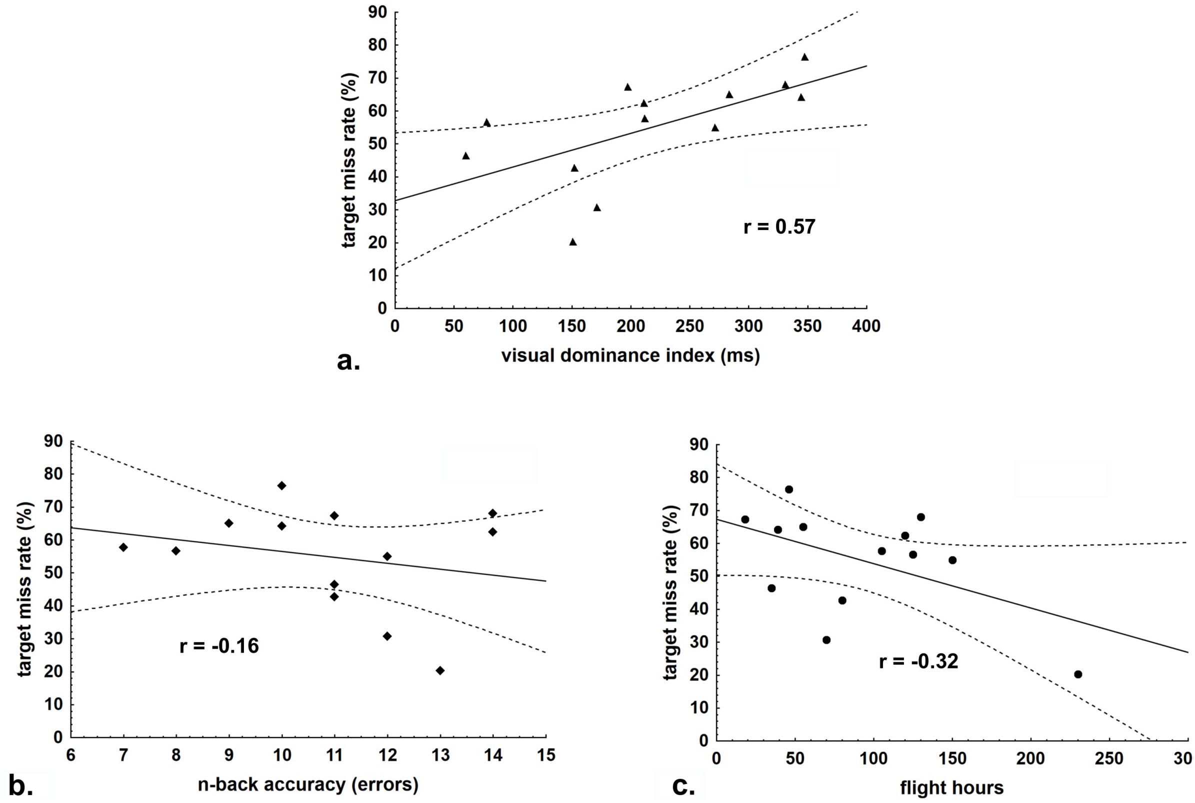

Figure 5. Oddball accuracy during the high load scenario as a function of **a.** the visual dominance index in the spatial audiovisual conflict task, **b.** the working memory ability and **c.** the flight experience. Semi-partial correlations are reported.

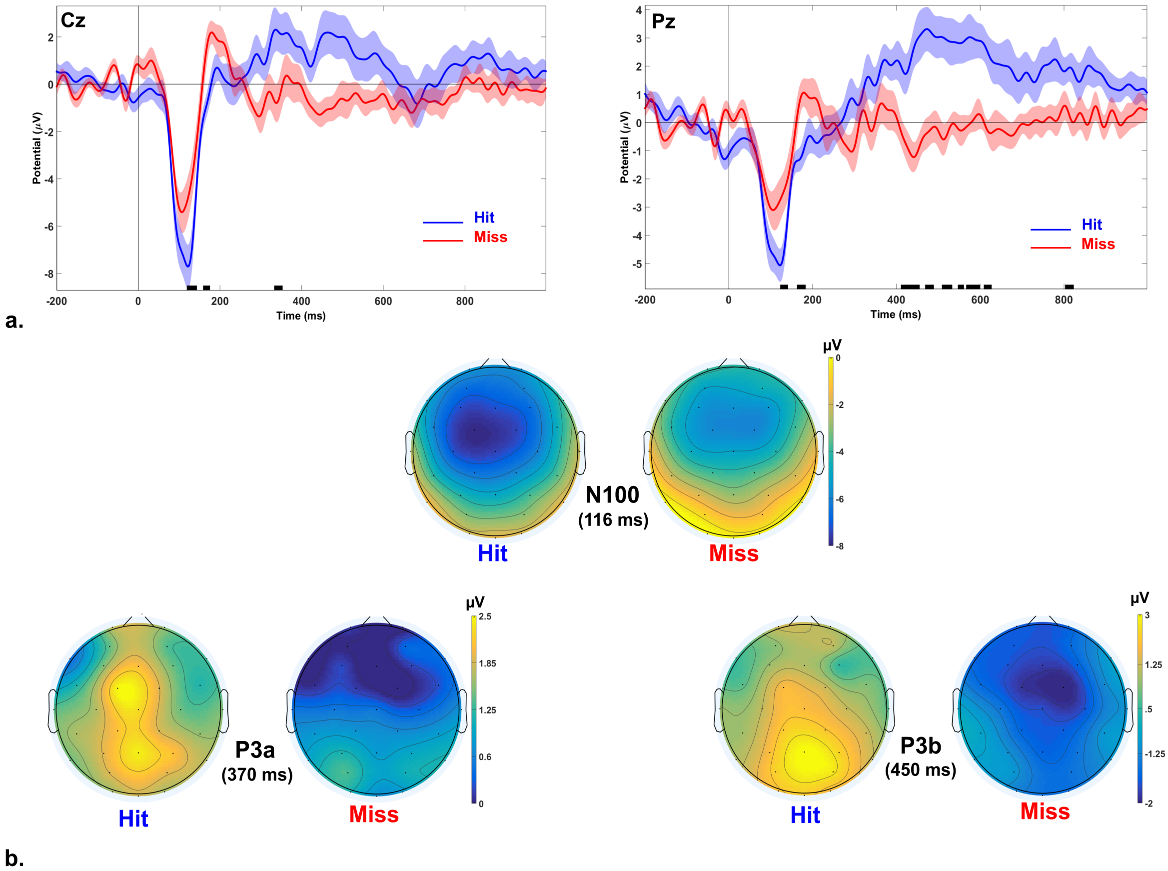

Figure 6. Group ERP results. **a.** Averaged ERPs for hit and missed auditory targets in the difficult flying scenario at Cz (left) and Pz (right) electrodes. Shapes represent the group standard deviations. Black lines at the x axis represent the significant differences between hit and miss (permutation test; $p<0.05$; FDR corrected). **b.** 2-D topographical views for hit and missed auditory targets at 116 ms (up, N100), 370 ms (left, P3a) and 450 ms post-stimulus (right, P3b).

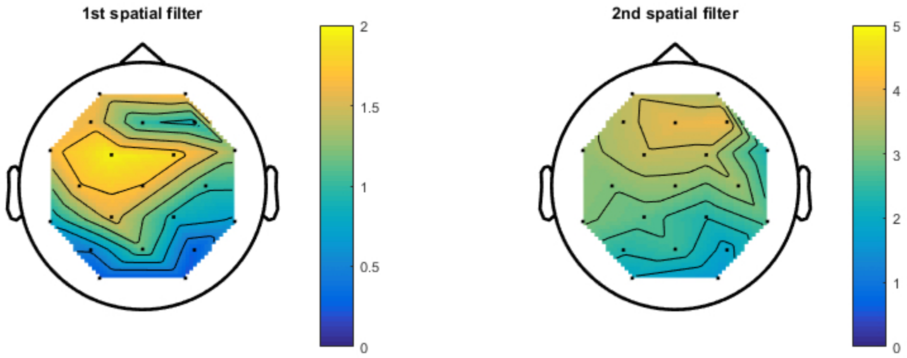

Figure 7. Spatial patterns of the two CCA filters used to enhance discriminability between classes.