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## EEG/ERP as a measure of mental workload in a simple piloting task

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### Abstract

Operating an aircraft is cognitively challenging: pilots have to control the plane and must remain responsive to potential verbal-auditory stimuli (e.g. Air Traffic Control Communication) and auditory alerts (e.g. Terrain Awareness and Warning System). Fifteen participants had to control an aircraft in order to target one of three differently-colored aircrafts displayed on a computer screen. The name of the color (written in black ink) corresponding to the aircraft to target was displayed in the center of the screen. Simultaneously with the onset of the written name of the color, a spoken color name distractor that participants had to ignore was played. This auditory distractor was either congruent (10%, spoken color name matched the written color) or incongruent (10%, spoken color name did not match the written color). The task difficulty varied in terms of working memory load with an n-back-like sub-task. In the low load condition, participants had to target the aircraft corresponding to the currently presented written instruction (n = 0). In the high load condition, participants had to target the aircraft corresponding to the instruction presented two trials before (n = 2). Behavioral analysis showed that increased mental workload provoked a decrease in piloting performance, i.e. participants tended to forget the correct instruction. On the physiological level, EEG/ERP measurements related to instructions showed that increased mental workload was accompanied by lower P3b amplitude. We assume that the lower P3b amplitude reflects the depletion of the cognitive resources allocated to the processing of the instructions. These results suggest that P3b can be a relevant indicator of the openness of the system to sudden and unexpected critical stimuli such as auditory alerts.

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**Keywords:** Aviation safety, Electroencephalography, Cognitive workload, Auditory alerts

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## 1. Introduction

Operating an aircraft is cognitively challenging: pilots have to fly the aircraft and navigate while remaining responsive to potential verbal-auditory stimuli (e.g. Air Traffic Control Communication) and auditory alerts (e.g. Terrain Awareness and Warning System). Previous researches from cognitive psychology emphasized that individuals in attention-demanding settings can remain unaware of unexpected stimuli [1-4]. An important amount of studies demonstrates that attentional capacity may be shared by both visual and auditory modalities [5-7]. To this extent, when engaged in a visual task associated with a high perceptive charge, an individual may be less likely to process an auditory stimulus when presented at the same time. In the same way, several authors showed that an increased cognitive load can provoke a reduced “openness” of the attentional system to distractors [8-10]. Generally used in static laboratory tasks, the interference paradigm is an interesting way to measure this phenomenon. In this paradigm, a target is accompanied by a visual or an auditory distractor item. The participant is asked to react to the target as quickly as possible while attempting to ignore the distractor. Depending on the relation between the target and the distractor, the target processing may be slowed down or accelerated. Traditionally, the available attentional resources can be evaluated by measuring the level of interference caused by the distractor stimulus at a behavioral level (i.e. accuracy and response times). According to Lavie [11], high load on “frontal” cognitive control processes increases distractor processing. Available attentional resources can be also examined at an electrophysiological level (i.e., brain reaction to visual and auditory stimuli), according to [8-10], reduced openness in an interference paradigm is associated with a lower P300 amplitude, an event related potential (ERP) associated with both cognitive and attentional processes [12].

The present study aims at testing the impact of cognitive load and incongruence on the processing of relevant instruction during a dynamic piloting situation in combination with EEG/ERP measurements. Participants had to continuously control an aircraft in order to target one of three differently-colored aircrafts displayed on a computer screen. The black inked color name corresponding to the color of the aircraft to target was displayed in the center of the screen while a spoken color name distractor that participants had to ignore was played. The task difficulty varied in terms of working memory load with an n-back-like sub-task. In the low load condition, participants had to target the aircraft corresponding to the currently presented written instruction ( $n = 0$ ). In the high load condition, participants had to target the aircraft corresponding to the instruction presented two trials before ( $n = 2$ ).

We examined the following questions: a) How do cognitive load and incongruence affect the processing of the target instruction and consequently the piloting performance? b) Is there any interaction effect between cognitive load and incongruence? c) How do these two factors influence brain activity observed through the amplitude of the P300 component.

## 2. Material and methods

### 2.1. Ethic statement

All participants were informed of their rights and gave written informed consent for participation in the study, according to the Declaration of Helsinki. The research was carried out fulfilling ethical requirements in accordance with the standard procedures of the ISAE Supaero.

### 2.2. Participants

Fifteen French male participants ( $M_{Age} = 24.6$ ,  $SD \pm 1.86$ ) participated in this study. All were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971), had normal auditory acuity and normal or corrected-to-normal vision. None of the participants reported a history of prior neurological disorder.

### 2.3. Aviation task

Participants had to continuously control an aircraft using a joystick in order to target one of three differently-colored aircrafts displayed on a computer screen. The name of the color (written in black ink) corresponding to the

aircraft to target was displayed for 1000ms in the center of the screen every 4500 ms. Simultaneously with the onset of the written name of the color, a spoken color name distractor that participants had to ignore was presented during 280 ms. This auditory distractor was either congruent (10%, spoken color name matched the written color), incongruent (10%, spoken color name did not match the written color) or neutral (10%, no aircraft on the screen corresponded to the spoken color name). A frequent spoken color name was also presented (70%, always “gray”). The task difficulty varied in terms of working memory load with an n-back-like sub-task. In the low load condition, participants had to target the aircraft corresponding to the currently presented written instruction ( $n = 0$ ). In the high load condition, participants had to target the aircraft corresponding to the instruction presented two trials before ( $n = 2$ ) (Figure 1). The quality of target aircraft pursuit was indicative of participants' piloting performance. We computed accuracy for each condition as a percentage of correct aircraft targeting. We considered that an aircraft was followed correctly if the distance between the user's aircraft and the target one was inferior to 100 pixels and it remained below this threshold for the 90% of the remaining trial length.

#### 2.4. Procedure

Participants were seated comfortably in a reclining armchair in a dimmed and sound-dampened experimental room. The task was displayed on a high-resolution computer located at eye level 70 cm in front of the participant. Participants were first trained for the two difficulty conditions using two sets of 20 trials. They were then equipped with the EEG electrode cap as well as the Electro-OculoGraphic (EOG) electrodes (blinks or saccades detection) and went through the two experimental blocks of 250 trials each. Immediately after each block, participants filled out the NASA Task Load Index (NASA TLX, [13]) questionnaire (Figure 2). This questionnaire provides an evaluation of the subjective mental demand elicited by the task for each level of difficulty.

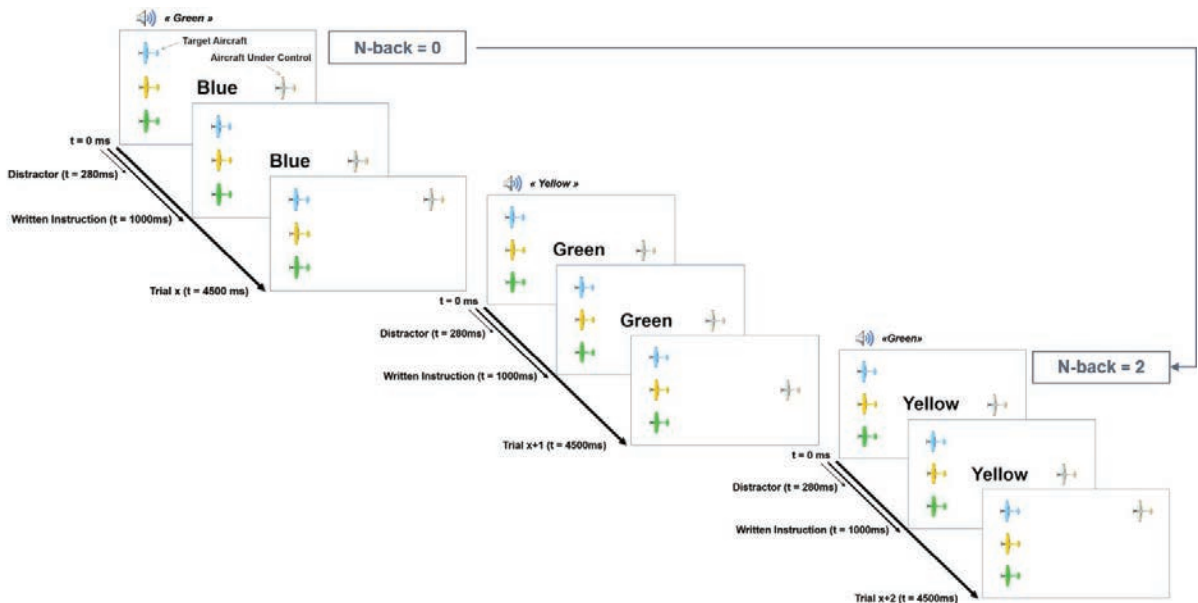


Fig. 1. In the low load condition (n-back 0), participants had to immediately target the aircraft corresponding to the currently presented written instruction “blue”. In the high load condition (n-back 2), participants had to target the blue aircraft two trials later. The auditory distractor was played for 280 ms while the written instruction was displayed for 1000ms. Each trial lasted for 4500 ms.

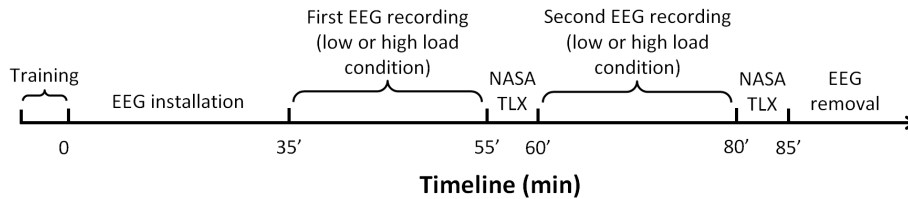


Fig. 2. Timeline of the experiment. The whole procedure lasted 85min, including 5 min training, 30min to install the EEG sensors, 40 min of EEG recording and 10 min to fill the two NASA TLX questionnaires.

## 2.5. Electroencephalography

EEG was amplified and recorded with a ActiveTwo BioSemi system (BioSemi, Amsterdam, The Netherlands) from 30 Ag/AgCl active electrodes (<http://www.biosemi.com>) mounted on a cap and placed on the scalp according to the International 10–20 System (FP1, FP2, AF3, AF4, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, CP5, CP1, Cz, CP2, CP6, P7, P3, Pz, P4, P8, T7, T8, PO3, PO4, O1, Oz, O2) plus two sites below the eyes for eye movement monitoring. Two additional electrodes placed close to Cz, the Common Mode Sense [CMS] active electrode and the Driven Right Leg [DRL] passive electrode, were used to form the feedback loop that drives the average potential of the participant as close as possible to the AD-box reference potential. Electrode impedance was kept below 5 k $\Omega$  for scalp electrodes, and below 10 k $\Omega$  for the four eye channels. Skin-electrode contact, obtained using electro-conductive gel, was monitored, keeping voltage offset from the CMS below 25 mV for each measurement site. All the signals were (DC) amplified and digitalized continuously with a sampling rate of 512 Hz with an anti-aliasing filter with 3 dB point at 104 Hz (fifth order sinc filter); no high-pass filtering was applied online. The triggering signals to each word onset were recorded on additional digital channels. EEG data were off-line re-referenced to the average activity of the two mastoids and band-pass filtered (0.1 – 40 Hz, 12 dB/octave), given that for some subjects the low-pass filter was not effective in completely removing the 75Hz artifact. Epochs were time locked to the offer presentation and extracted in the interval from - 200ms to 1000ms. Segments with excessive blinks and/or artefacts (such as excessive muscle activity) were eliminated off-line before data averaging. The lost data (due to artefacts) were equal to 7%. A 200 ms pre-stimulus baseline was used in all analyses.

## 3. Results

### 3.1. Behavioral results

A  $2 \times 2$  ANOVA (Congruence [Congruent; Incongruent]  $\times$  Load [Low; High]) revealed a main effect of the load on the piloting performance, the participants were better at aircraft targeting for the low load condition compared to high load condition [ $F(1, 14) = 8.15, p < .05, \eta p^2 = .37$ ; see Figure 3]. On the contrary, we found no effect of congruence, [ $F(1, 14) = 1.52, p = .22$ ], neither Load  $\times$  Congruence interaction [ $F(1, 14) = 1.08, p = .37$ ] on the piloting performance.

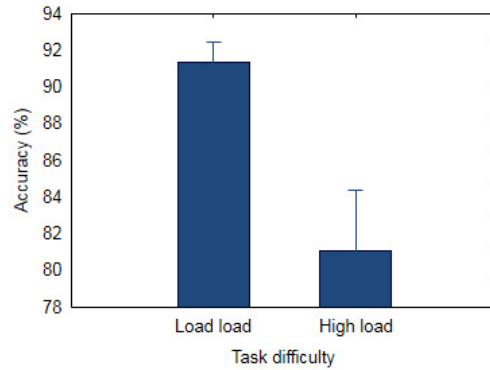


Fig. 3. Mean accuracy for low and high load conditions. Error bars indicate S.E.M.

### 3.2. NASA-TLX questionnaire

A  $2 \times 2$  ANOVA (Congruence [Congruent; Incongruent]  $\times$  Load [Low; High]) showed a significant difference between the low load and the high load conditions on the mental demand dimension of the NASA-TLX (Figure 4), [ $F(1, 12) = 40.53, p < .001, \eta^2 = .77$ ]. Participants estimated the high load condition as more mentally demanding ( $M = 73.5, SD = 4.2$ ) compared with the low load condition ( $M = 34.6, SD = 6.2$ ).

### 3.3 EEG/ERP P300 analyses

The P300 amplitude (more precisely the P3b) was assessed in terms of mean amplitude in the 400 – 450 ms time window (Figure 5). A  $3 \times 2 \times 2$  (Electrode [Fz, Cz, Pz]  $\times$  Congruence [congruent, incongruent]  $\times$  Load [low, high]) ANOVA was conducted. Tukey's HSD tests were used for post-hoc contrasts. The analysis revealed a main effect of load [ $F(1, 14) = 5.18, p < .05, \eta^2 = .27$ ], with a greater P3b amplitude in low load ( $M = 3.96 \mu V, SD = 7.52$ ) than in high load ( $M = 1.27 \mu V, SD = 6.28$ ). The analysis also revealed a significant Electrode  $\times$  Congruence interaction [ $F(2, 28) = 4.24, p < .05, \eta^2 = .23$ ], with a greater P3b amplitude for incongruent trials ( $M = 1.40 \mu V, SD = 7.21$ ) than for congruent trials ( $M = - .61 \mu V, SD = 7.89, p < .05$ ) at Fz but not at Cz (incongruent trials:  $M = 2.38 \mu V, SD = 6.57$ ; congruent trials:  $M = 2.11 \mu V, SD = 7.80, p = .99$ ) and at Pz (incongruent trials:  $M = 5.13 \mu V, SD = 4.95$ ; congruent trials:  $M = 5.29 \mu V, SD = 7.00, p = .99$ ).

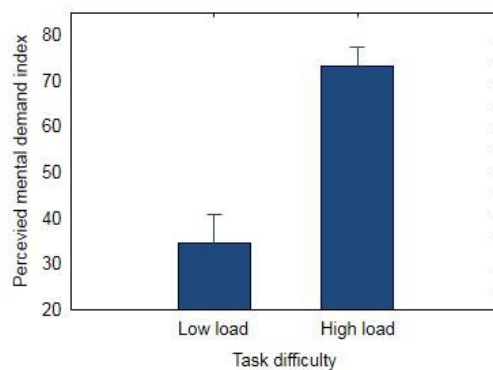


Fig. 4. Mean index of perceived mental demand for low and high load conditions. Error bars indicate S.E.M.

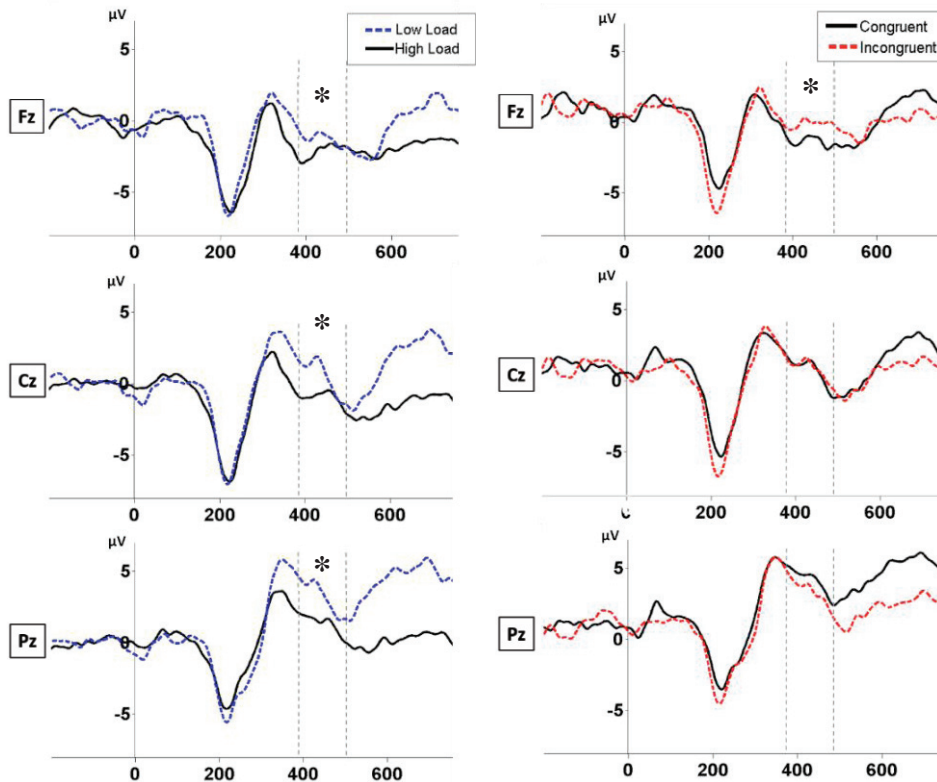


Fig. 5. Grand average ERP waveforms A) for low load (dotted blue line) and high load (black line); B) for congruent (black line) and incongruent trials (dotted red line) at Fz, Cz and Pz electrodes. The horizontal axis denotes time in milliseconds (ms), with the P300 time windows used for the indicated analysis, and the vertical axis denotes amplitude in microvolts ( $\mu\text{V}$ ). Negative is plotted down; Zeros on the timeline indicate the onset of both the written instruction and the auditory distractor.

#### 4. Discussion

In the present study we investigated how working memory load impacted the processing of important visual instruction during a dynamic piloting task. We also investigated how concurrent auditory task-irrelevant stimuli (distractors) interfered with the piloting task whether they were congruent or not with the written instruction. Finally, we investigated how these two factors influence brain activity observed through the amplitude of the P3b component.

The higher level of difficulty (n-back 2) provoked both a decrease in piloting performance and an increase in subjective workload (i.e., NASA TLX questionnaire). The manipulation of the load in working memory was effective in that higher memory load made the task more difficult to perform; in particular, to correctly maintain and manipulate the instructions in working memory. At an electrophysiological level, the ERPs revealed that the amplitude of the P3b was higher in the low load condition than in the high load condition. The P3b has been regarded as a sign of processes of memory access that are evoked by evaluation of stimuli in tasks that require some form of action like a covert or overt response [14], ecologically close to instruction or alerts occurring in a cockpit. Diminished amplitude of the P3b response to visual and auditory instructions (we cannot dissociate ERP related to written instruction from ERP related to auditory distractors) is expected when the task at hand requires more processing or working memory [15]. Taken together, these behavioral and electrophysiological results demonstrate that the increase in cognitive load may have led to a reduced openness of the attentional system, and at least partially disrupted the encoding and maintenance of the relevant visual information (i.e., written instruction).

Our EEG results also demonstrated that P3b was sensitive to the congruency/incongruence between the written instruction and the auditory distractor. Incongruent distractors elicited larger P300 for the Fz electrode. However it did not result in a significant behavioral interference. As participants were required to make a response in all trials to target a new aircraft, it is likely that they put more effort in the evaluation of the relevant stimuli—the written instruction—to perform the correct action. This increase in P3b amplitude with incongruent auditory distractors seems to emphasize that more resources were recruited to cope with the interference. This hypothesis is supported by the fact that the piloting performances were not impacted by the interference.

In conclusion, our findings suggest that P3b can be an efficient tool to measure cognitive load in ecological settings. In the present study we adapted the auditory-visual interference to a simple piloting task. In this context, cognitive load tracked by P3b was load on memory induced by different task difficulties and effort of resisting to irrelevant auditory stimuli. On one hand, P3b amplitude decreased when participants' resources allocated to the processing of instruction diminished under load, which resulted in diminished performance. On the other hand, P3b amplitude increased when participants' resources allocated to the processing of instruction increased to resist to interference, which resulted in preserved performance.

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