Using Near Infrared Spectroscopy to Detect Mental Overload in Flight Simulator

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ABSTRACT

Piloting requires high level of cognitive control, especially in demanding situations. When cognitive functions are overloaded, no more sufficient resources are available to manage the situation. As a consequence, it is important to have a valid measurement tool of pilots' online workload. In this research, we used a BIOPAC 16 channel fNIRS to monitor prefrontal activity of eleven airline student pilots during two landing scenarios (easy and difficult) in a flight simulator. As expected, results from subjective measurements revealed that the perceived cognitive mental effort was higher during the difficult landing. The right dorsolateral prefrontal cortex (DLPFC) demonstrated the highest concentration changes of oxy-hemoglobin (O2Hb) during both scenarios, with the difficult landing inducing higher concentration changes than the easy landing. These results demonstrate the sensitivity of fNIRS to detect mental overload in complex and ecological scenarios. The findings of this study may be applied to real-time monitoring of the pilot mental workload as well as the evaluation and the certification of new cockpit designs.

Keywords: functional near infrared spectroscopy, cognitive workload, aviation safety, flight performance

INTRODUCTION

Piloting is a complex activity that takes place in a dynamic and rapidly changing environment. In such a context, high level cognitive functions are vital abilities for handling the aircraft, interpreting the instrument parameters, maintaining up-to-date situation awareness and making relevant decisions. These functions, which are traditionally labelled executive functions or cognitive control, are known to involve the prefrontal cortex (Dalley, Cardinal, & Robbins, 2004; E. Miller & Wallis, 2009; E. K. Miller & Cohen, 2001), the latter being also involved in decision making in uncertain environments, including the navigation task (Yoshida & Ishii, 2006). Despite its impressive capabilities, human brain exhibits severe capacity constraints in information processing. The neural basis for such limitations has been demonstrated in various neuroimaging studies (Charron & Koechlin, 2010; Dux, Ivanoff, Asplund, & Marois, 2006). When cognitive functions are overloaded, which is often the case when the context is unfamiliar, uncertain or when time pressure is high, the pilots performance can be lessened (Durantin et al. 2013). Worse, they may face cognitive tunneling, defined as the inability of the operator to reallocate his/her attention from one task to another (Thomas & Wickens, 2001). In such a situation, they are more likely to commit an error and to miss critical information such as visual or auditory warnings (Dehais et al., 2012; Dehais et al., 2013).

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So, in critical systems where performance decline can result in catastrophic losses, it could be vital to monitor the operator's mental workload. For example, detection of the operator's cognitive incapacity may be used to trigger alerts or adapt the level of automation in extreme situations. Also, situations of low mental workload may follow flight phases of extreme activity, which increases the complexity in the adjustment of the operator's level of vigilance. A promising way to detect mental underload/overload is to monitor the prefrontal lobes online. Functional Near Infrared Spectroscopy (fNIRS) is an increasingly popular technique for observing the brain functioning. This technology has recently been used in fundamental research (Mihara, Miyai, Hatakenaka, Kubota, & Sakoda, 2008), clinical studies (Ehlis, Bähne, Jacob, Herrmann, & Fallgatter, 2008), aging (Kwee & Nakada, 2003) and human factors studies (Ayaz et al., 2012 ; Solovey et al., 2011). Contrary to more common neuroimaging techniques such as functional magnetic resonance imaging, fNIRS allows *in vivo* imaging in ecological conditions with natural freedom of movement and in complex environments such as high-fidelity simulators. So, this technique should allow detecting mental workload changes of human operators placed in realistic and critical situations.

The objective of the present study was to validate that prefrontal activity measured through fNIRS technology, could be sensitive to an increase of mental workload in an ecological flight situation. More precisely, we used fNIRS technology to monitor prefrontal activity of eleven airline student pilots during two landing phases in a flight simulator: an easy landing, supposed to correspond to a medium workload and a difficult landing, supposed to simulate a high workload situation.

MATERIAL AND METHODS

Participants

Eleven airline pilot students (élèves pilotes de ligne, EPL) from the Ecole Nationale de l'Aviation Civile (ENAC) (mean age: 20.6, SD = 1.1, all male) completed the two flight scenarios. After providing informed consent, they were all briefed on the simulator and the experiment task.

fNIRS equipment

During the entire duration of each flight scenario, hemodynamics of the prefrontal cortex was recorded with the functional Near Infrared Spectrometer fNIR100 (Biopac) equipped with 16 optodes (Figure 1). Each optode recorded the hemodynamics at a frequency of 2 Hz with a 2.5 cm source-detector separation.

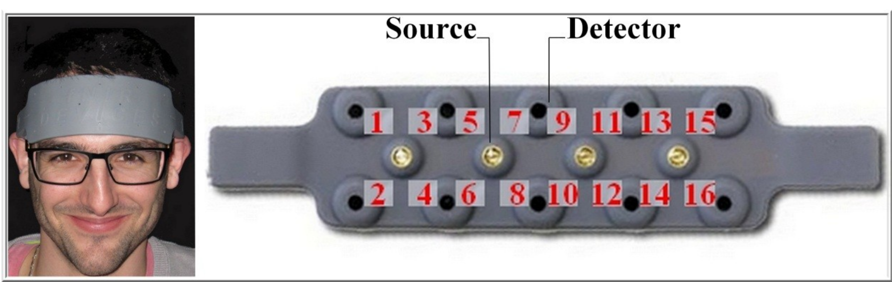

Figure 1. fNIR100 headband and associated optodes numbering

Flight scenarios

Before the experiment, to familiarize them with the flight simulator (Figure 2), each participant underwent a training session consisting of two landings on the same landing field: one with external visibility and no crosswind, another with external visibility and a moderate crosswind. During the experiment itself, participants performed two landing scenarios of different cognitive demands (easy and difficult). The order in which the landing scenarios were performed was counterbalanced across participants. All landings occurred on a simulation of the 14R runway at Blagnac airport (Toulouse, France). The initial conditions were defined as follows: 2500 feet altitude, heading 142 degrees, 130 knots, starting 6 miles from the airfield threshold. In both scenarios, the instrument landing system (ILS) was available to help perform the approach. In the easy landing scenario, the external visibility was perfect and there was no crosswind whereas in the difficult landing scenario, there was no external visibility (dense cloud layer) above 100 feet above the ground and there was a strong crosswind. The difficult landing condition was intended to load more heavily on the executive functions than the easy one.

Immediately after the end of each flight scenario, participants completed a subjective mental workload evaluation on a 1-7 scale. This simplified procedure has shown to be significantly correlated with the NASA Task Load Index (TLX) questionnaire (Causse, Faaland, & Dehais, 2012). The total experiment duration was approximately one hour.

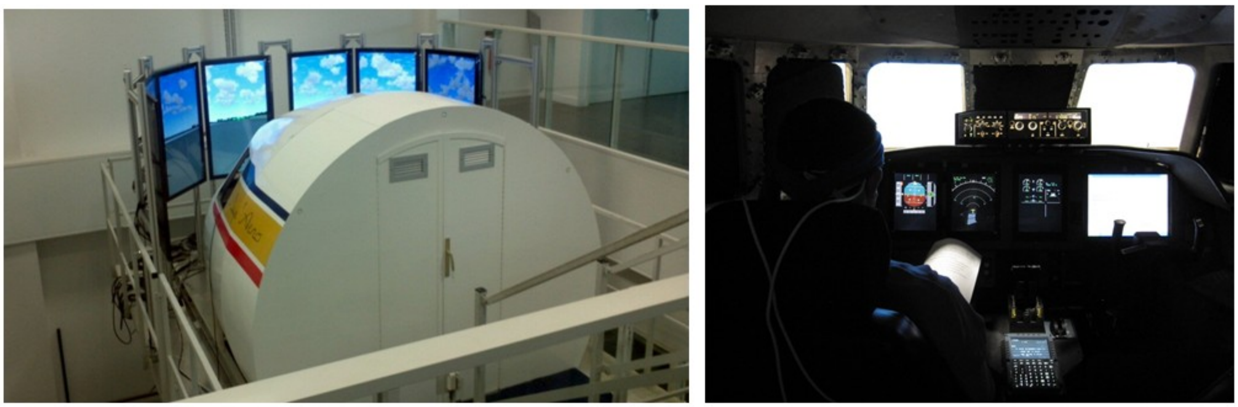

Figure 2. Left: outside view of the ISAE flight simulator; Right: inside view of the flight simulator with a participant equipped with the fNIRS.

Data Analysis

A one-way repeated measures ANOVA was used to compare the mental workload perceived by the participants during the two scenarios. Regarding the fNIRS, for each participant, the variations in light absorption at two different peak wavelengths (730 nm and 850 nm) were used to calculate changes of O2Hb and HbR (both in µmol/L) using the modified Beer–Lambert Law (MBLL). Concentration measurements were band-pass filtered (pass band: 0.012Hz to 0.33Hz) with a finite impulse response, linear phase filter with order of 20 to further remove any slowly drifting signal components and other noise with other frequencies than the target signal (Roche-Labarbe et al., 2008). Saturated channels (if any) were excluded. In this paper, we focused our analysis on O2Hb changes, HbR concentrations were not examined. O2Hb concentration changes from a ten-second rest period baseline (performed before each flight scenario) were averaged over the whole time course of each flight. Average O2Hb change for each scenario was used as the dependent measure and submitted to a two-way repeated measures ANOVA (2 flight scenarios * 16 optodes).

RESULTS

Self-reported ratings of workload

Subjective mental workload was significantly higher in the difficult landing than in the easy landing (F(1, 10) = 43.62, $p < .001$, $\eta^2_p = .81$), indicating that the scenario difficulty manipulation was successful, see Figure 3. Coherently, in the difficult scenario, the flight performance (glide slope deviation) was degraded in comparison to the easy landing (F(1, 10) = 4.30, $p = .017$, $\eta^2_p = .45$), see Figure 4.

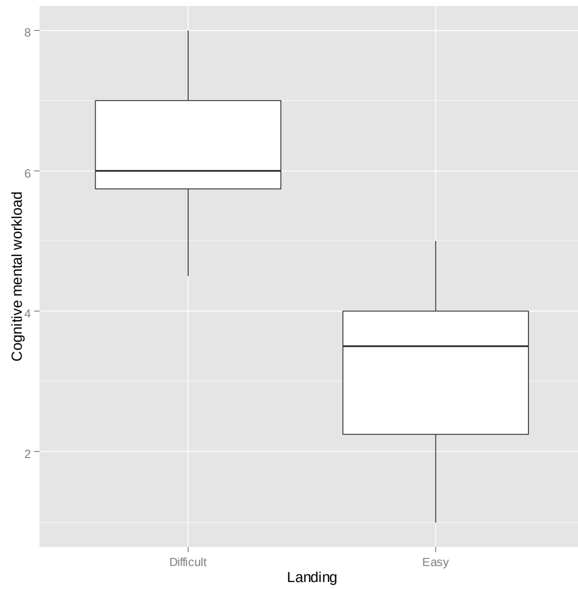

Figure 3. Boxplots of the subjective cognitive mental workload during the two different flight scenarios. The difficult landing successfully elicited a higher cognitive mental workload than the easy landing.

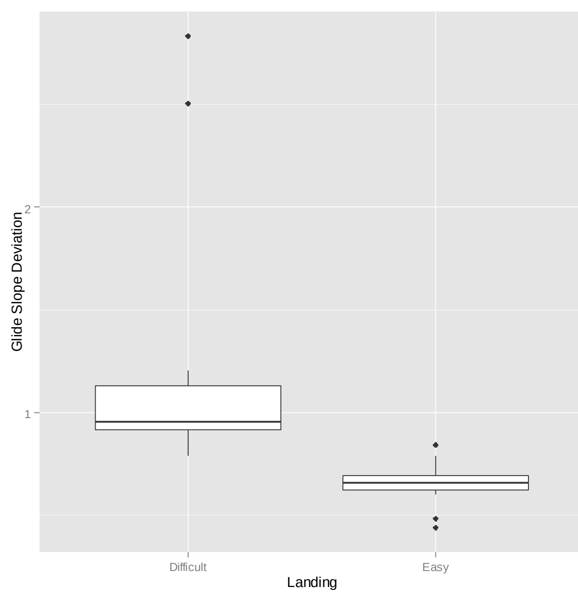

Figure 4. Boxplots of the glide slope deviation during the two different flight scenarios. In the difficult scenario, the flight performance was degraded in comparison to the easy landing.

fNIRS measurements

The two-way repeated measures ANOVA showed a significant main effect of the scenario, the difficult landing provoked a higher O2Hb concentration change ($F(1, 10) = 10.17$, $p = .009$, $\eta^2_p = .50$), see Figure 5. There was also a main effect of the optode location ($F(15, 150) = 2.42$, $p = .003$, $\eta^2_p = .20$). In particular, optode #16 (see Figure 6), in the area of the right dorsolateral prefrontal cortex (DLPFC), demonstrated a higher concentration change of O2Hb than several other optodes (i.e. optodes #1, #3, #4, #5, #9, #11, #13; Tukey's honestly significant difference, $p < .05$) during both scenarios, see Figure 5. A scenarios * optodes interaction was also found ($F(15, 150) = 1.99$, $p = .019$, $\eta^2_p = .17$), highlighting a greater increase in concentration change of O2Hb during the difficult landing for optode

#16 than for the other optodes (see Figure 5 also). Taken together, these two last results (main effect of optode location and scenarios * optodes interaction) revealed that the landing situation involves primarily the right DLPFC and even more when landing is difficult.

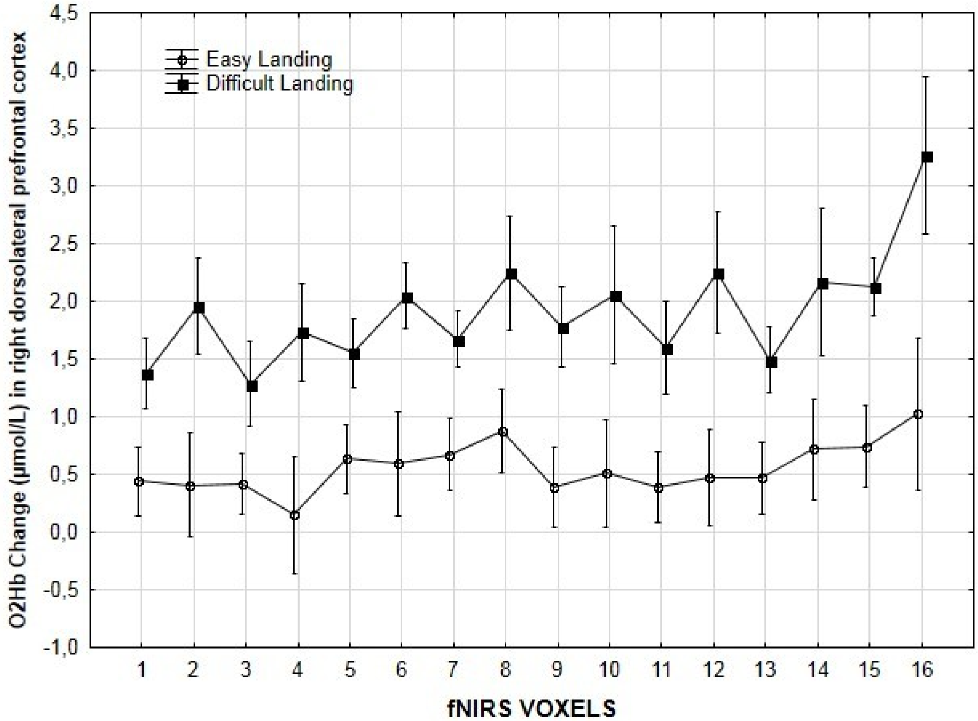

Figure 5. Mean HB02 concentration change from a ten-second rest period baseline, during the two different flight scenarios as a function of the 16 fNIRS voxels. Bars represent the standard error of the mean.

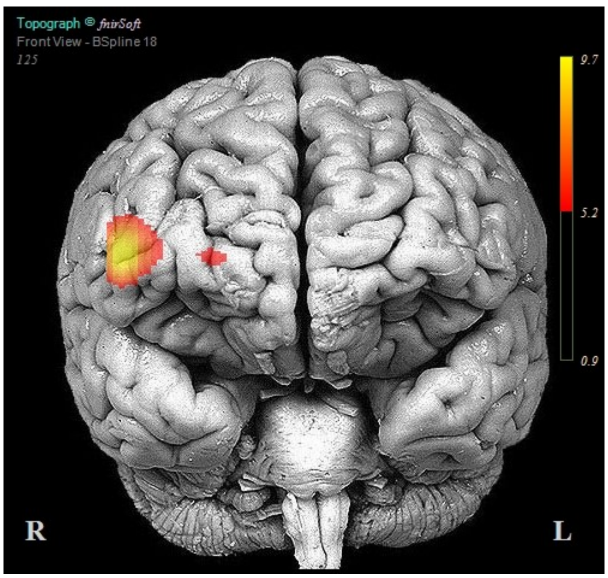

Figure 6. Illustration of the global effect of the difficult landing scenario (i.e., mean activation for the task vs. the baseline) for one participant. A large right dorsolateral prefrontal cortex activation was found.

CONCLUSION

Neuroergonomics attempts to provide sensitive and reliable assessment of human mental workload in complex work environments (eg. Causse et al., 2013; Dehais, Causse, & Pastor, 2008; Gagnon et al., 2012; Giraudet, St-Louis, & Causse, 2012; Parasuraman, 2011) through the use of operationally-relevant tasks (Parasuraman, 2003). Our study was clearly grounded in this approach and aimed to examine brain mechanisms underlying flight performance through brain hemodynamics of future professional pilots. As expected, results from subjective measurements revealed that the perceived cognitive mental effort was higher during the difficult landing. The DLPFC was the region that demonstrated the highest concentrations of O2Hb during both scenarios. In addition, fNIRS measurements showed significantly higher right DLPFC concentrations of O2Hb for the difficult landing than for the easy scenario. Coherently, in the difficult scenario, the flight performance (glide slope deviation) was degraded in comparison to the easy scenario. With this work, we have demonstrated that the measurements obtained with fNIRS agree with self-reported measurements of workload.

On the whole, these findings demonstrated the sensitivity of fNIRS to detect mental load variations in a complex and ecological set up. A continuous real-time monitoring of pilot mental workload would be of great interest to provide feedback information to the operator himself or to the automated system he is interacting with. The introduction of intelligent adaptive systems that can adjust the mental workload by taking charge of a wide variety of tasks (Kaber & Endsley, 2004 ; Scerbo, 2007) while letting the operator focus on high level tasks is a relevant application of real-time monitoring of the mental workload through psychophysiological measurement (Byrne & Parasuraman, 1996). Indeed, in some hazardous situations where the operator is vulnerable, it would be useful for the system to detect the mental overload in order to invoke, for example, more automated tasks. In contrast to subjective measurements, continuous questioning of the operator's subjective mental workload would be counterproductive, as it would likely and unnecessarily increase the cognitive load.

The present study has highlighted the potential use of the fNIRS technology to provide continuous, non-interfering data sampling to assess mental workload. This study could also have implications for the evaluation and certification of new cockpit designs. Introduction of new cockpit designs may have unexpected consequences, such as an increase of the pilot's mental workload when placed in a particular context. For instance, fNIRS technology would permit an objective assessment and comparison of the mental workload induced by two different designs. Subsequently, this use of fNIRS could be one step of the certification process. Globally, if future cockpit designs are better adapted to the human brain, it will have a positive impact on aviation safety.

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