Theta Neurofeedback and Pilots' Executive Functioning

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Introduction – Piloting an aircraft is a complex and multitasking activity that requires a high degree of excutive functioning. For instance, pilots have to manage several tasks in a dynamic environment, select, store and update critical information while being able to exercise mental flexibility to adapt to external contingencies (Causse et al., 2011). However, stressors such as fatigue, mental overload and stress can impair pilots' executive functioning and, in return, jeopardize flight safety (Causse et al., 2011; Dehais, Hodgetts, et al., 2019; Dehais, Roy, et al., 2019; Régis et al., 2014). Several solutions ranging from adaptive automation to the design of cognitive countermeasures have been suggested to mitigate those deleterious states (Causse et al., 2012; Dehais et al., 2011; Prinzel et al., 2000). A complementary approach is to consider the use of preventive solutions such as neurofeedback (NF). Indeed, NF displays cerebral activity in real time using brain imaging techniques (e.g., EEG, fNIRS, fMRI) in order to teach individuals to self-regulate their brain functioning crucially involved in cognitive aspects (Enriquez-Geppert et al., 2017; Scharnowski & Weiskopf, 2015). Recent works have highlighted that NF training is particularly relevant to improve performance in controlled settings (Nan et al., 2013; Reiner et al., 2014) as well as more ecological contexts (Ring et al., 2015; Xiang et al., 2018). In addition, it has been shown that frontal-medial theta [4-8] Hz, which is regarded as the "working language" for neural communication of executive functioning can improve executive functions (Enriquez-Geppert et al., 2014).

The main objective of this study is to investigate NF as a tool to enhance executive functioning with pilots. Our hypothesis are, that NF would lead to increased fm-theta, to improved executive functioning in basic task, and ecological tasks, which is in the end associated to good performance in a flying simulator. To our knowledge, we use for the first time a systematic approach of three levels, in which tasks are used that measure EF a) as purely as possible in a controlled lab setting, b) with a more ecological task, c) the involvement of EF in during piloting in a flying simulator. We also investigated the effect of the combination of NF training and a curative countermeasure in the last stage of the study.

Materials and Method – Twelve student-pilots at ISAE-SUPAERO were recruited for that study so far (30 expected). They were randomly divided into two groups (active group and sham group). The participants from the NF group underwent eight 1h30 training sessions consisting of six 5-min experimental blocks, plus a pre and a post baseline). During each session, the participants were equipped with a 32 active wet-electrode (500 Hz) EEG system positioned according to the 10-20 system in order to record their brain activity. A visual feedback (square) was displayed on a screen and changed its color according to the quantity of theta oscillations produced by the participants from red (low theta amplitude) to green (high theta amplitude) (see Figure 1A for an illustration). Participants were instructed to keep the square green as long as possible. The sham group received similar instructions, underwent the same protocol but instead of their own brain activity, received a sham which was operationalized as a reply from a participant of the experimental group.

Before and after the NF training sessions, both groups had to perform two cognitive tasks as illustrated in Figure 1B. The first one is the hybrid executive function task which is based on a previous study (Enriquez-Geppert et al., 2013). It was designed to separately assess the aforementioned executive functions at a fundamental level through scores and reaction times. The second one is the Multi-Attribute Task Battery (MATB-II) (Comstock & Arnegard, 1992) which mimics some aspects of piloting an aircraft (e.g., tracking, communications, resource management, conflict monitoring); see Figure 1C. During this task, behavioral and eye-tracking data were collected. Finally, a last session in a flying simulator was added at the end of the protocol (see Figure 1B and Figure 2). Again, the participants were equipped with the same EEG device. The task consisted in navigating through several waypoints as fast as possible and performing two secondary tasks at the same time: 1) active auditory oddball task (i.e. clicking on a trigger when the rare sound was presented) 2) managing the radio communications that consisted in an auditory working memory task. When the performances to one of the two secondary tasks started to be degraded, an adaptive assistance solution was proposed and offered the pilot to delegate one of the two tasks to automation. If no answer was given after 10s, the system took over by interrupting on of the secondary tasks randomly (Figure 2).

Results and discussion – First of all, preliminary results revealed that the active group exhibited higher amplitude of theta compared to the sham group. Additionally, our findings indicated a) lower reaction times after NF training for the active group in the memory updating and task switching subtasks of the hybrid test. Regarding the data collected from the MATB task, we observed b) better performances for the active group after the NF training for the conflict monitoring, the resource management and the communications tasks compared to the sham group. Finally, the experiment conducted in the flight simulator indicated that c) the active group obtained better navigation performance and was more accurate for the secondary tasks leading to less adaptive assistance than the sham group. Taken together, fronto-medial (fm) NF training appears a promising solution to improve both pilot's executive functioning and flying performance.

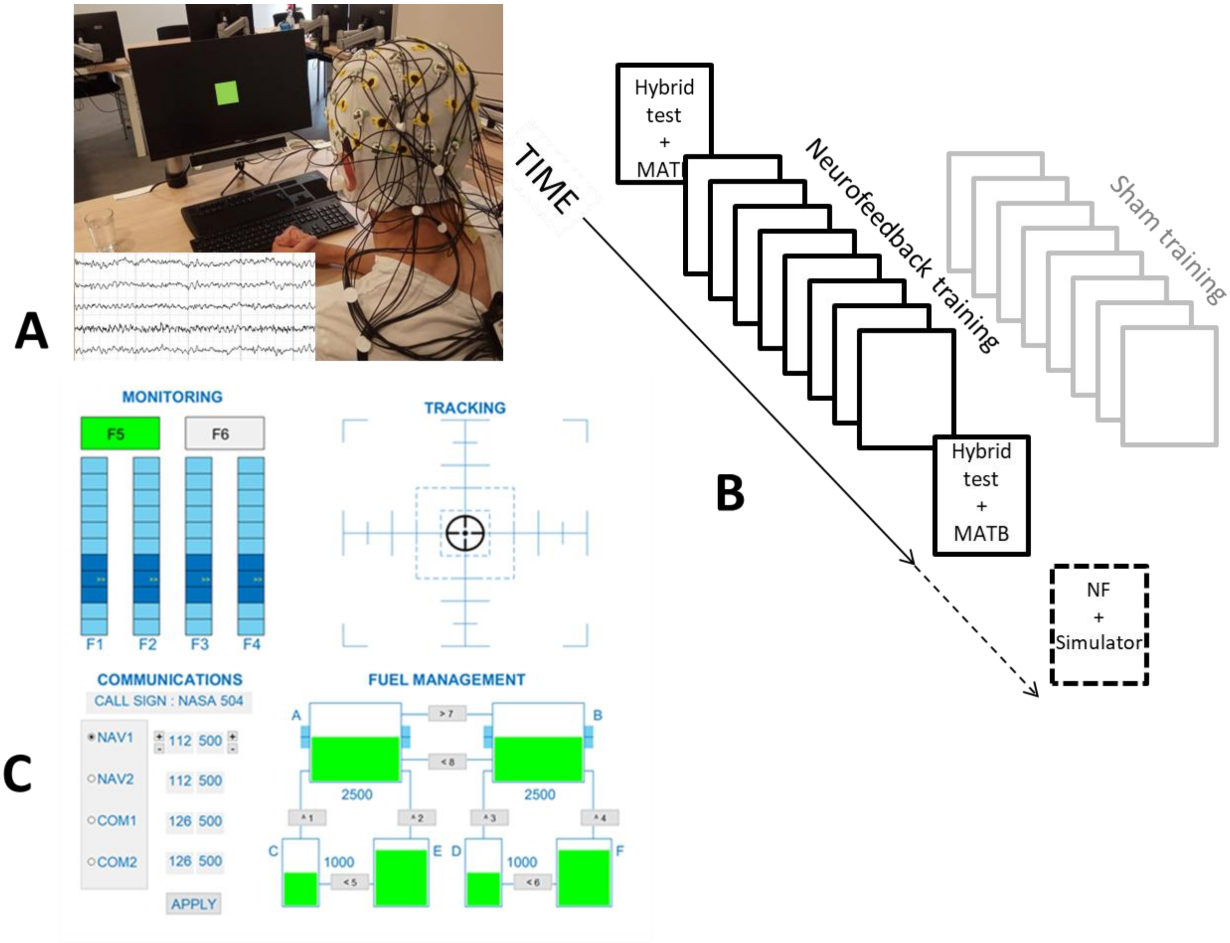

Figure 1. Illustration of a neurofeedback session. Participants comfortably sat in a chair and had to try to control a colored square on a screen in front of them thanks to their brain activity. They had to keep the square as green as possible as long as possible. The square was a representation of their fm-theta amplitude for neurofeedback group (high fm-theta amplitude gave a saturated green). In contrast, the variation of the colored square was a playback of a matched participant from the neurofeedback group for the sham group (**A**); Illustration of the protocol for both the experimental groups (**B**); Illustration of the four subtasks of the Multi-Attribute Task Battery (MATB-II): MONITORING task in the upper left corner where participants had to respond as quickly as possible to lights and scale fluctuations via keystrokes, TRACKING task in the upper right corner where participants to keep a circle as close to the center with a joystick, COMMUNICATIONS task in the bottom left corner where participants had to only answer broadcast messages that correspond to their call name and FUEL MANAGEMENT task in the bottom right corner that required participants to keep tanks' levels as close to 2500 as possible via managing eight pumps (**C**)

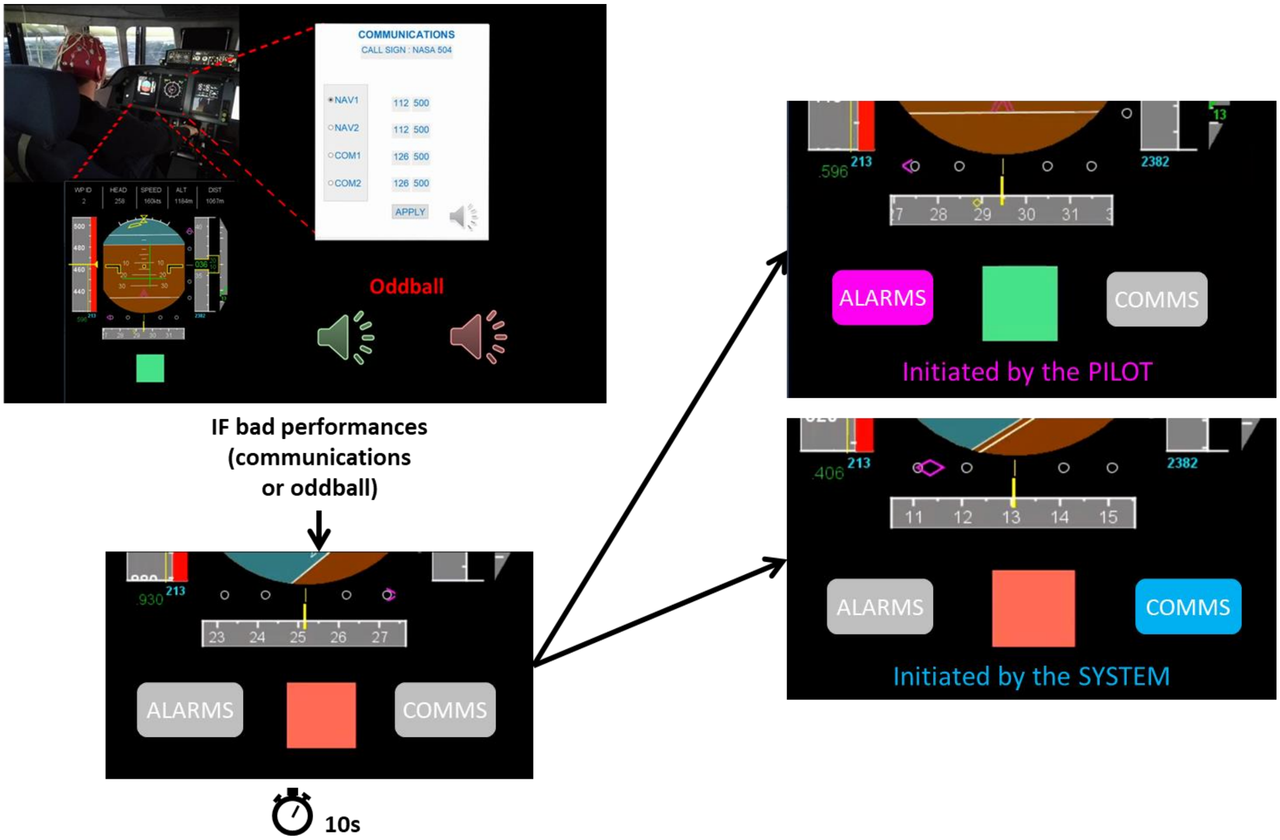

Figure 2. Illustration of the cockpit interfaces and the way the pilot aid is triggered. The upper left figure mainly represents the cockpit interfaces. It is composed of two touchscreen graphic interfaces: the primary flight display that contains basic information allowing flying and encompasses a colored square analogous to the one in the training sessions as well as an interface allowing answering to the communication task. In the same figure, one can also find an illustration of the auditory oddball which is the second subtask in this last stage of the protocol. If performances to one of the secondary tasks (communication and oddball) were too much degraded, two buttons appeared on both sides of the colored square as illustrated in the bottom left figure. Participants had then 10 s to press one of those buttons to stop one subtask for 30 s. If so, the button turned purple and the message “initiated by the pilot” appeared below the colored square as illustrated in the upper right figure. On the other hand, if no button was pressed within the 10 s, the system randomly stopped one of the two secondary tasks for 30 s as shown in the bottom right figure.

References:

Causse, M., Dehais, F., & Pastor, J. (2011). Executive Functions and Pilot Characteristics Predict Flight Simulator Performance in General Aviation Pilots. *The International Journal of Aviation Psychology*, *21*(3), 217-234. https://doi.org/10.1080/10508414.2011.582441

Causse, M., Phan, J., Ségonzac, T., & Dehais, F. (2012). *Mirror neuron based alerts for control flight into terrain avoidance*. 157-166. http://www.crcnetbase.com/doi/abs/10.1201/b12313-22

Comstock, J. R., & Arnegard, R. (1992). *The multi-attribute task battery for human operator workload and strategic behavior research*. https://ntrs.nasa.gov/search.jsp?R=19920007912

Dehais, F., Causse, M., & Tremblay, S. (2011). Mitigation of Conflicts with Automation : Use of Cognitive Countermeasures. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *53*(5), 448-460. https://doi.org/10.1177/0018720811418635

Dehais, F., Hodgetts, H. M., Causse, M., Behrend, J., Durantin, G., & Tremblay, S. (2019). Momentary lapse of control : A cognitive continuum approach to understanding and mitigating perseveration in human error. *Neuroscience & Biobehavioral Reviews*, *100*, 252-262. https://doi.org/10.1016/j.neubiorev.2019.03.006

Dehais, F., Roy, R. N., & Scannella, S. (2019). Inattentional deafness to auditory alarms : Inter-individual differences, electrophysiological signature and single trial classification. *Behavioural Brain Research*, *360*, 51-59. http://oatao.univ-toulouse.fr/21710/1/Dehais_21710.pdf

Enriquez-Geppert, S., Huster, R. J., & Herrmann, C. S. (2013). Boosting brain functions : Improving executive functions with behavioral training, neurostimulation, and neurofeedback. *International Journal of Psychophysiology*, *88*(1), 1-16. https://doi.org/10.1016/j.ijpsycho.2013.02.001

Enriquez-Geppert, S., Huster, R. J., & Herrmann, C. S. (2017). EEG-Neurofeedback as a Tool to Modulate Cognition and Behavior : A Review Tutorial. *Frontiers in Human Neuroscience*, *11*, 51. https://doi.org/10.3389/fnhum.2017.00051

Enriquez-Geppert, S., Huster, R. J., Scharfenort, R., Mokom, Z. N., Zimmermann, J., & Herrmann, C. S. (2014). Modulation of frontal-midline theta by neurofeedback. *Biological Psychology*, *95*, 59-69. https://doi.org/10.1016/j.biopsycho.2013.02.019

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex « Frontal Lobe » tasks : A latent variable analysis. *Cognitive Psychology*, *41*(1), 49-100. https://doi.org/10.1006/cogp.1999.0734

Nan, W., Wan, F., Lou, C. I., Vai, M. I., & Rosa, A. (2013). Peripheral visual performance enhancement by neurofeedback training. *Applied Psychophysiology and Biofeedback*, *38*(4), 285-291. https://doi.org/10.1007/s10484-013-9233-6

Prinzel, L. J., Freeman, F. G., Scerbo, M. W., Mikulka, P. J., & Pope, A. T. (2000). A Closed-Loop System for Examining Psychophysiological Measures for Adaptive Task Allocation. *The International Journal of Aviation Psychology*, *10*(4), 393-410. https://doi.org/10.1207/S15327108IJAP1004_6

Régis, N., Dehais, F., Rachelson, E., Thooris, C., Pizziol, S., Causse, M., & Tessier, C. (2014). Formal Detection of Attentional Tunneling in Human Operator–Automation Interactions. *IEEE Transactions on Human-Machine Systems*, *44*(3), 326-336. https://doi.org/10.1109/THMS.2014.2307258

Reiner, M., Rozengurt, R., & Barnea, A. (2014). Better than sleep : Theta neurofeedback training accelerates memory consolidation. *Biological Psychology*, *95*, 45-53. https://doi.org/10.1016/j.biopsycho.2013.10.010

Ring, C., Cooke, A., Kavussanu, M., McIntyre, D., & Masters, R. (2015). Investigating the efficacy of neurofeedback training for expediting expertise and excellence in sport. *Psychology of Sport and Exercise*, *16*, 118-127. https://doi.org/10.1016/j.psychsport.2014.08.005

Scharnowski, F., & Weiskopf, N. (2015). Cognitive enhancement through real-time fMRI neurofeedback. *Current Opinion in Behavioral Sciences*, *4*, 122-127. https://doi.org/10.1016/j.cobeha.2015.05.001

Xiang, M.-Q., Hou, X.-H., Liao, B.-G., Liao, J.-W., & Hu, M. (2018). The effect of neurofeedback training for sport performance in athletes : A meta-analysis. *Psychology of Sport and Exercise*, *36*, 114-122. https://doi.org/10.1016/j.psychsport.2018.02.004