Behavioural and cortical responses to visuo-spatial working memory task using fNIRS.

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Introduction

Working memory (WM) plays an important role in pilots since they have to continuously integrate and dynamically update information within a rapidly changing environment (Verdière, Roy & Dehais, 2018). WM is essential for overcoming response conflict and optimal selective attention performance. Yet, WM is a capacity-limited system, and some authors suggested that increasing the demands on WM reduces the ability to ignore irrelevant stimuli and can lead to decreased performance in dual–tasking (Lavie & Cox, 1997). Conversely, Simon et al. (2016) suggested that increased WM load is associated with enhanced protection from distraction. The heterogeneity of behavioural paradigms used makes it difficult to discern our understanding of the effect of task difficulty on brain activity and behavioural performance, in the context of WM. To address the conflicting accounts, we aimed to setup a dual-task paradigm similar to the real-world as encountered when piloting a plane. A spatial N-Back task was built concurrently with an auditory detection task. Then, we examined how changes in task difficulty was modulating functional brain activation and effective connectivity (Sun et al., 2019) in some important brain areas involved in WM (i.e., the medial and dorsolateral prefrontal cortex, mPFC and dlPFC). We reasoned that WM-related activation and connectivity would vary in proportion to the task difficulty.

Methods

Sixteen healthy volunteers (mean age ± SD, 24 ± 4 years, 10 females) performed a dual-task paradigm after a learning phase for allowing the normalization of participants' performance and the suppression of strategy related behavioural variability. The primary task was a spatial N-back task at three difficulty levels (1-back, 2-back and 3-back). A blue square was consecutively and pseudo-randomly displayed in a grid in one out of nine possible locations every 1,750 ms. Participants had to report when the current square position matched a previous one. The lag between the sample and the presently displayed stimulus depended on the level of difficulty. The secondary task consisted of auditory detection task with sounds randomly presented throughout. Participants had to fill a NASA-TLX questionnaire (Hart & Staveland, 1988) and a STAI-S short-form questionnaire (Marteau & Bekker, 1992), to assess mental workload and anxiety state, respectively.

Hemodynamic changes (relative concentration of oxygenated O_2Hb and deoxygenated HHb-haemoglobin) were recorded at 10Hz from a fNIRS system (Octamon, Artinis Medical Systems, The Netherlands) suited for mPFC and dlPFC measurements. The system consisted of a headband with 8 light emitters and 2 detectors, with an interoptode distance of 3.5 cm. After transforming the raw light intensities collected with the Oxysoft software (v3.2.75) into optical density (light absorption variation), we performed a pre-processing of the data to reduce the different types of artefacts present in O_2Hb and HHb signals. First, we removed the motion artefacts using Savitsky-Golay spline method (Jahani et al., 2018) implemented in HOMER toolbox (Huppert et al., 2009). The resulting optical densities were then converted to relative concentrations of O_2Hb and HHb. A bandpass filter (butterworth 4th order) with a cut-off frequency [0.009-0.5] was then applied to limit physiological artefacts contained in the signals. Following a slicing of the fNIRS signals from events indicating the onset of each n-back condition, the data was centred to zero at the time of the event. Then, the mean of the resulting time series between 0 to 35s after the event was extracted.

The Directed Functional Connectivity (DFC) was also computed between all the channels. We used a multivariate autoregressive modelling and extracting the frequency band of interest [0.009-0.01] with the spectral Granger Causality approach implemented in the MVGC toolbox (Barnett & Seth, 2014). The Granger causality using fNIRS has been shown to be reliable compared to other neuroimaging methods (Anwar et al., 2016) and has been already used to investigate changes in inter-hemispheric information flow over PFC depending on the difficulty in a classic n-back task (Sun et al., 2019). All fNIRS analyses were performed in Matlab® (MATLAB 2015a, The MathWorks, USA).

Result and discussion

At the behavioural level, signal-detection analysis showed a lesser sensitivity for 3-back compared to 1-back and 2-back. Reaction times were slower for 3-back compared to 1-back and 2-back. The resulting behavioural efficacy for 3-back was lower than 2-back and 1-back conditions, as well as for 2-back compared to 1-back (Fig. 1A). Sensitivity for the auditory task was lower for 3-back than 1-back ($P=0.051$), and higher ($P=0.016$) for test phase relative to learning phase.

At the subjective level, the NASA-TLX score significantly increased according to the n-back conditions; no changes were observed for the anxiety state.

At the cortical level, no significant differences were observed for O_2Hb changes but greater changes in left and right PFC for HHb (i.e., increased for mPFC and dlPFC and decrease for one channel in mPFC) were observed for 2-back and 3-back compared to 1-back ($P<0.05$, Fig. 1B).

For Granger Causality, our results for O_2Hb showed an increase of the DFC between 1-back and 2-back and a global decrease between 1-back compared to 2-back and 3 back. As expected (Sun et al., 2019), inter-hemispheric information flow increases from right dlPFC -> left dlPFC with the difficulty of the task (but only between 1-back vs 2 back) (Fig. 1C). However, higher connections were present from left mPFC -> right mPFC as well as decrease from dlPFC left -> dlPFC right (1-back vs 3-back), reflecting a different complex network organisation involved in the task. Finally, inter-brain connections for HHb observed could be a complementary marker of the task difficulty.

Taken together, fNIRS might be sensitive enough to assess hemodynamic responses (restricted here to PFC) directly related to cognitive processes elicited by a visuo-spatial WM task combined to an auditory secondary task. Interestingly, this study showed that the magnitude of O_2Hb and HHb signals associated to Granger Causality approach can be the cortical manifestation of cognitive performance limitation in the face of excessive WM load. More precisely, our results highlighted significant inter hemispheric differences dependent of the task difficulty.

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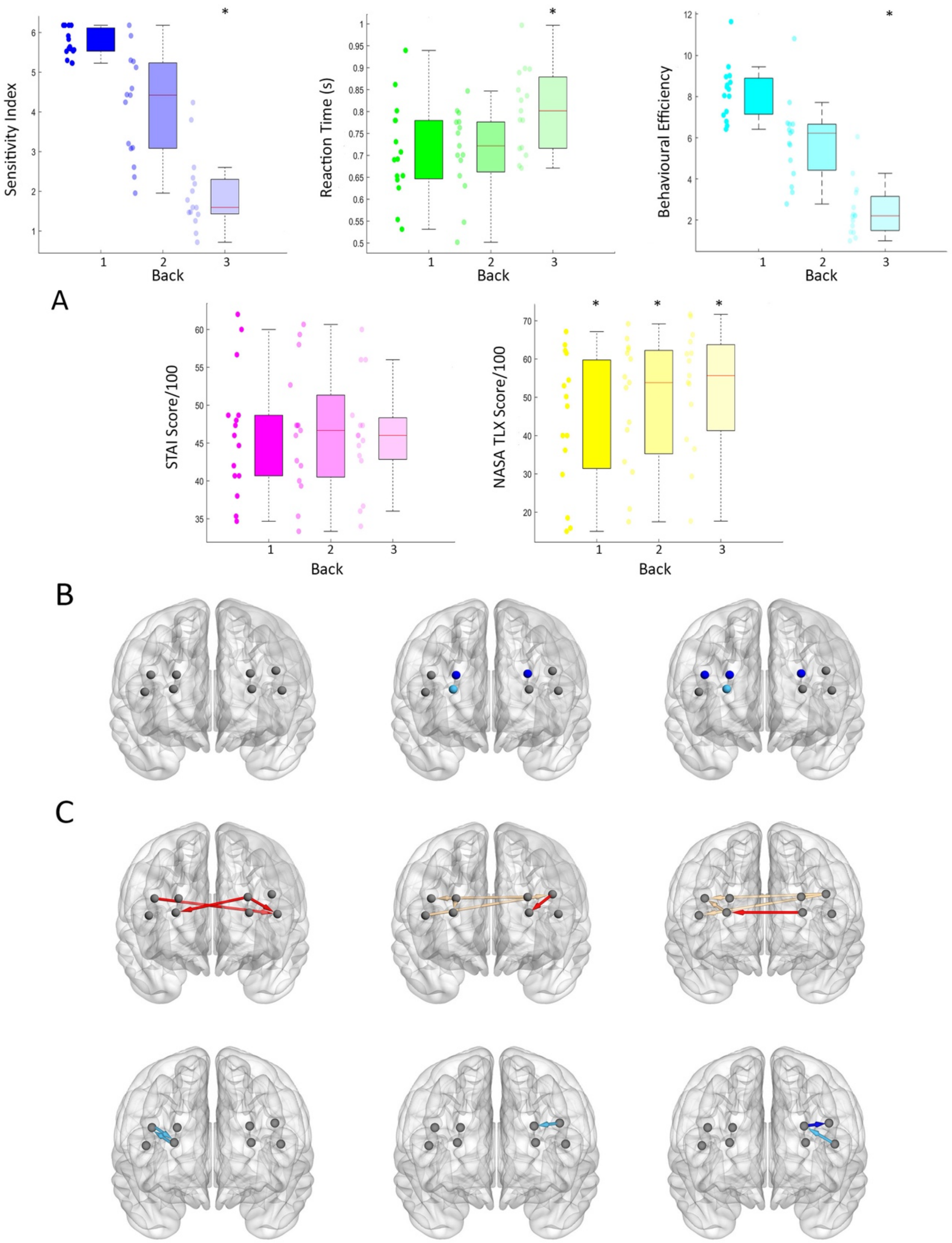

*Figure 1: A) Individual and median values for sensitivity index, reaction time and behavioural efficiency in top, anxiety state (STAI) and mental workload (NASA TLX) in the bottom for n-back task level of difficulty (1,2 and 3 back). B) Significative difference in relative changes in mean HHb concentration for: 1-back vs 2-back in left, 2-back vs 3-back in the middle and 1-back vs 3-back in right. Dark blue dots represent an increase of mean HHb concentration, light blue dots represent a decrease and grey dots represent no significant results. C) Significant Granger Causality between channels for O_2Hb in top and HHb in bottom. The arrow indicates direction. Dark red and blue arrows represent a significant increase while light blue and yellow represent a decrease between conditions with 1-back vs 2-back in left, 2-back vs 3-back in the middle and 1-back vs 3-back in right. * $P < 0.05$.*

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