To cite this version: Causse, Mickael and Peysakhovich, Vsevolod and Mandrick, Kevin Eliciting Sustained Mental Effort Using the Toulouse N-Back Task: Prefrontal Cortex and Pupillary Responses. (2016) In: Advances in Neuroergonomics and Cognitive Engineering. (Advances in Intelligent Systems and Computing). Springer International Publishing, pp. 185-193. ISBN 978-3-319-41690-8

Eliciting sustained mental effort using the Toulouse N-back Task: prefrontal cortex and pupillary responses

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Abstract. In safety-critical environments such as piloting or air-traffic control, the study of mental overload is crucial to further reduce accident rates. However, researchers face the complexity of inducing an important amount of mental effort in laboratory conditions. Therefore, we designed a novel paradigm, named "Toulouse N-back Task" (TNT), combining the classical n-back task with a mathematical processing to replicate the multidimensional sustained high mental workload (MW) existing in many complex occupations. Instead of memorizing and comparing unique items, as in classical n-back task, participants have to memorize and to compare the results of mathematics operations. Twenty participants were tested with the TNT under three load factors (n = 0, 1, or 2) with functional Near-InfraRed Spectroscopy (fNIRS) and pupillary measurements. The results revealed that higher difficulty degraded the cognitive performance together with increased prefrontal oxygenation and an increase in pupil diameter. Hence, hemodynamic responses and pupil diameter were sensitive to different levels of TNT's difficulty. This paradigm could serve as a viable alternative to the classical n-back task and enable the progressive increase of the difficulty, for example, to test "high performer" individuals.

Keywords: Neuroergonomics · Mental workload · Toulouse N-back Task · Prefrontal Cortex · Near-Infrared Spectroscopy · Pupillometry ·

1 Introduction

In the neuroscientific literature, one of the most used experimental tasks for the study of working memory (WM) is the n-back task [see 1]. It involves monitoring, updating, and manipulation of information and is assumed to heavily tax several key processes within WM. The parametric modulation of task difficulty via the load factor $n \in \{0, 1, 2, 3, ...\}$ without modifying the visual input or motor responses made it widely used as a tool to manipulate mental workload in applied studies [e.g., 2,3-6]. Moreover, cognitive performance during this task is sensitive to several conditions such as stress

[7,8] or fatigue [9]. Implicitly, one considers the WM load during n-back paradigm as a key component and a reasonable approximation of mental workload, which is likely true to some extent. However, when a study requires increasing the information processing demand, which is high in many safety-critical occupations (e.g., aircraft piloting), the n value can be too high (e.g., 3-back) and participants often disengage from the task. Therefore, we designed a novel paradigm, called "Toulouse N-back Task" (TNT), combining the classical n-back task with a mathematical processing to replicate the multidimensional sustained high mental WL existing in many safety-critical occupations (e.g., pilots). The task enables the progressive increase of the difficulty to reach a high mental load, for example, to test "high performer" individuals. Instead of memorizing and comparing unique items, as in classical task, the participants have to memorize and to compare the results of mathematics operations, computed beforehand. Mathematical problems are either subtractions or additions of 2-digits numbers, multiples of 5 for ease (e.g., 15 + 40; 90 – 35, etc.). The task also allows studying both tonic (during a block) and phasic (during mathematical processing) components of mental activity. This advantage of different time scale studies makes the task suitable for both low latency (such as phasic pupil response) and high latency signals (such as brain oxygenation or tonic pupil response). In this study, 20 participants were submitted to the TNT. Half of them were tested with pupillometry measurements and the other half were equipped with functional Near-InfraRed Spectroscopy (fNIRS). We measured the pupil diameter changes and concentration changes in oxygenated (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) over the prefrontal cortex (PFC). They performed several blocks at three load factors (n = 0, 1, or 2) by indicating the presence/absence of a target by a button press. In the 0-back condition, an arbitrary value of "50" was defined as the target. During the 1-back (2-back) condition, the target was a result that matched the result presented one trial (two trials, respectively) before.

2 Material and methods

2.1 Participants

Twenty healthy volunteers participated in the experiment. Pupillometric recordings were performed on 10 participants in study 1 (2 women, age 26.2 ± 4.2 years) and fNIRS recordings were performed on 10 other participants in Study 2 (2 women, age 25 ± 5.1 years). Participants were split into two separate studies as simultaneous near-infrared spectroscopy and pupillometry measurement is complex due to wavelength overlap in the infrared band of both techniques. All were students at Ecole Nationale de l'Aviation Civile (ENAC) and Institut Supérieur de l'Aéronautique et de l'Espace (ISAE) in Toulouse, France. None reported neither affective or anxiety disorder, nor any neurological or cardiovascular disease. None was under medication that might affect the brain or autonomic functions. All volunteers reported normal auditory acuity and normal or corrected-to-normal vision. All participants gave written informed consent in accordance with local ethical board committee.

2.2 Toulouse N-back Task

The novel mental arithmetic N-back task called Toulouse N-back Task (TNT) developed for this study combines a classical n-back task with mental arithmetic operations (Fig. 1). WM load varied between conditions with the n level. In each trial, volunteers were required to compute the result and compare it with either a fixed number (0-back), or the result obtained 1 (1-back) or 2 (2-back) trials before. Mathematical operations were either additions or subtractions of numbers always multiple of 5 (e.g., 15 + 40, 90 – 35). In addition to the three difficulty levels, rest period screens with "00 + 00" operations were presented. Volunteers did not give any response during this condition.

Operations were displayed in the center of a gray background. Participants were given a 2-button Cedrus response pad (RB-740, Cedrus Corporation, San Pedro, CA) and were asked to press either a green button if the result matched the target number or a red button if not. Participants had to give their responses as quickly as possible. The task was implemented in Matlab (MathWorks) using the Psychophysics Toolbox (Psychtoolbox 3, [10])

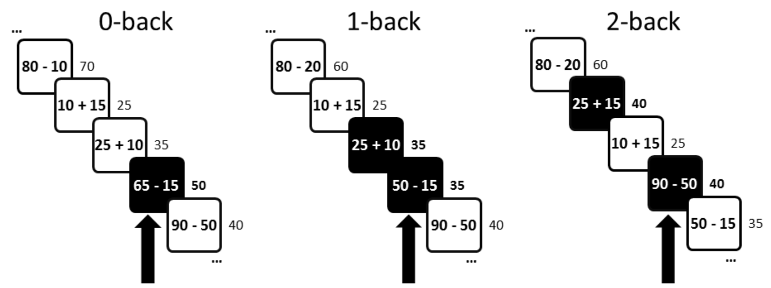

Fig. 1. Toulouse N-back Task. An example of trials for the TNT, in which subjects computed mental calculations combined with a N-back task. The 0-, 1-, and 2-back task blocks lasted 36 s, interleaved with 18 s rest periods. Subjects responded to targets and non-targets by pressing one of two different buttons. During the 0-back (left part of the figure), a simple comparison of the current result with "50" was required. During the 1-back (middle part of the figure) and the 2-back (right part) tasks, the current result had to be compared with the one presented 1 or 2 trials before, respectively. Black arrows indicate target trials.

The experiment included a total of 30 blocks, with 10 blocks for each of the three difficulty levels, presented in a pseudo-randomized order. A block lasted 36 s, and they were interleaved with 18 s rest periods. Stimuli were presented for 2 s with an inter-stimulus interval of 1 s. Each block contained 12 stimuli, with 4 targets in random positions. Following the training period with the TNT, participants rated the perceived difficulty using a DP15 scale [11]. The DP15 scale consists in a 15-point category scale, with 7 labels, from 2 (extremely easy) to 14 (extremely difficult), symmetrically placed around a central label 8 –somewhat difficult).

2.3 Behavioral measurements

Performance in the TNT was measured for each participant. TNT accuracy was calculated using the d-prime measure, computed as follows: Z(% hit rate) – Z(% false alarm rate). Additionally, response times were computed.

2.4 Study 1: Pupillometry measurements

Participants were seated at approximately 70 cm from a 22'' computer screen (1680 × 1250). Ambient luminance was of 10 lx. During the whole experiment, participants' gaze position and pupil diameter were tracked using a remote SMI RED500 eye-tracker (SensoMotoric Instruments GmbH, Germany) at a sampling rate of 120 Hz. This device allows tracking the pupil despite small head movements. Before each run, participants performed a 5-point calibration procedure validated with 4 additional fixation points. The data acquisition routine used iViewX SDK to communicate with Matlab software. Identified blinks and short periods of signal loss were linearly interpolated. Then the signal was filtered with a two-pass 9-point filter (low-pass with a cutoff frequency of 5.9 Hz). Pupil diameter analyses were performed upon the median pupil diameter value for each block.

2.5 Study 2: Functional near infrared spectrometry (fNIRS) measurements

To illuminate the forehead, a CW fNIRS 16-channel headband model 100 fNIRS system (fNIRS Devices LLC, Photomac MD; http://www.fnirdevices.com) was used to obtain raw light intensity by specific dual wavelengths of 730 nm and 850 nm. Data were acquired at a sampling frequency of 2 Hz.

At the beginning of the experiment, participants were fitted with the fNIRS headband. The baseline was taken while they relaxed with eyes closed. fNIRS-PFC activity was recorded through the entire experiment. COBI Studio software (Drexel University) was used for data acquisition and visualization. The version 4.0 of fnirSoft software package was used for filtering, converting and analyzing data [12]. First, the raw optical density signals were converted to concentration changes of oxy-Hb and deoxy-Hb using the modified Beer-lambert law. At this point, few channels with no signal were rejected automatically and individually (for one subject channel 5 and 11; for one subject channel 11; for one subject channels 5 and 15). fNIRS data were then bandpass filtered using a FIR filter of order 20 and cutoff frequencies of 0.01 and 0.1 Hz. No detrending was applied.

To dissociate effects of N-back task difficulty (0-back vs. 1-back vs. 2-back) in each region of interests (ROI), we extracted the fNIRS response from each block for the left, the center, and the right PFC. Signals were normalized towards zero by subtracting the current signal with the first data point. Then, signals were averaged on all trials for each condition. For fNIRS data analysis, we compared concentration changes in oxy-Hb signals calculating the slope index as suggested by Mandrick et al. [13] during the 36 s of each block. This index reflects the magnitude of the PFC oxygenation response for each ROI and task difficulty.

2.6 Data analysis

Results were analyzed using Statistica software (StatSoft). Group data were reported as means ± SD in the text and means + one SD in the figures. Normality and homoscedasticity of data were assessed using Kolmogorov-Smirnov. Data were analyzed using repeated-measures analyses of variance (ANOVA) for normally distributed variables (i.e., pupillary and fNIRS measurements, d', response times). In the case of significant main effect or interaction, significant differences between conditions were identified using Tukey's HSD post-hoc tests. A significance level of $p < .05$ was used for all comparisons. Effect sizes are reported using partial eta-squared (η_p^2).

3 RESULTS

3.1 Behavioral data

Participants demonstrated lower d' scores with increasing task difficulty ($F(2, 38) = 72.95$, $p < 0.001$). Post-hoc comparison revealed significant differences between 0-back and 1-back and between 1-back and 2-back ($p < .001$ in both comparisons). Similar results were observed for the response times, which increased with mental workload ($F(2, 38) = 38.94$, $p < 0.001$), see Fig. 2. Post-hoc comparison also revealed significant differences between 0-back and 1-back and between 1-back and 2-back ($p < .001$ in both comparisons).

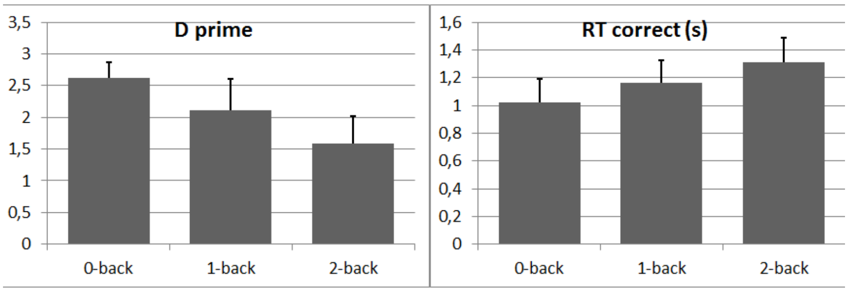

Fig. 2. Behavioral performance. N-back task scores for each level of difficulty (0-, 1-, and 2-back). Error bars indicate SD. Left- d prime calculated as z(hit rate) - z(false alarm rate). Right- reaction times. n = 20.

3.2 Pupillometric results

Participants demonstrated larger pupillary responses across level of task difficulty ($F(1, 9) = 14.70$, $p < 0.001$). Post-hoc comparison revealed significant differences between 0-back and 2-back and between 1-back and 2-back ($p < .001$ and $p < .05$ respectively), see Fig. 3.

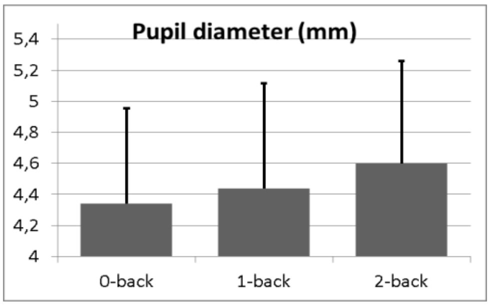

Fig. 3. Mean pupil diameter according to the TNT levels of difficulty (0-, 1-, and 2-back). Error bars indicate SD. n = 10.

3.3 fNIRS results

We found a significant interaction between brain region and level of difficulty on slope index for changes in oxy-Hb concentration ($F(4, 36) = 6.71$, $p < 0.001$). Post-hoc comparison revealed that difficulty did not significantly impact the center region of the PFC whereas significant differences were found on the right PFC with a significant difference between 0-back and 2-back ($p < 0.001$). Moreover, oxy-Hb concentration changes, in the 2-back condition, localized in right and left PFC were higher than in the center PFC ($p < 0.001$ in both comparisons) see Fig. 4.

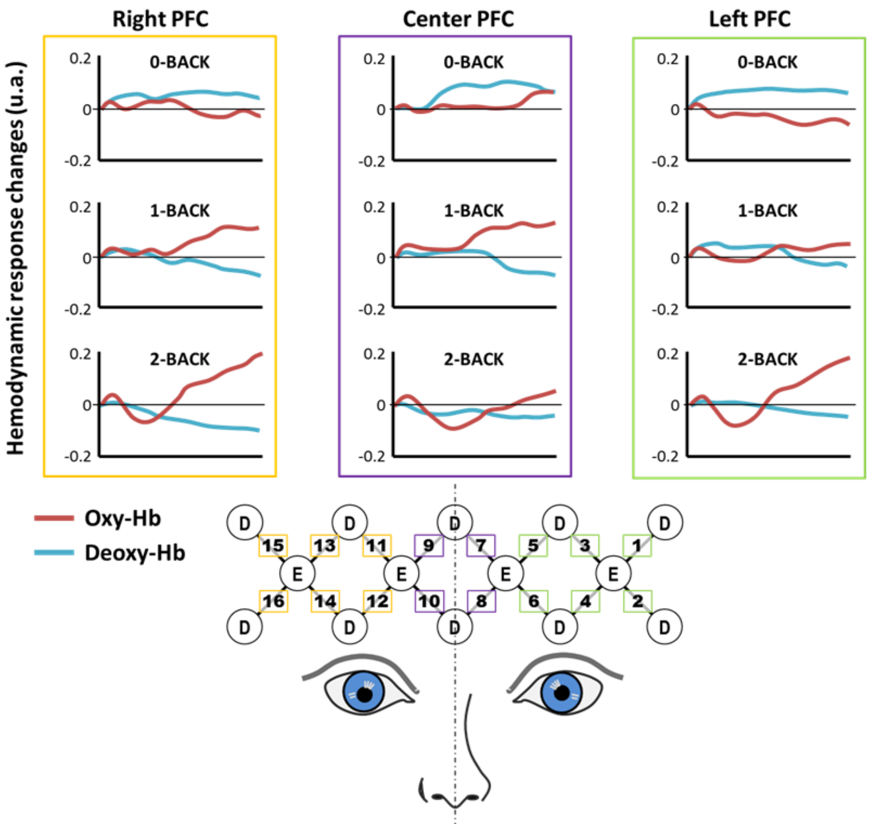

Fig. 4. Up: grand average of all 10 subjects in the three load of the TNT for the three ROIs. Red and blue lines indicate the changes of oxy-Hb and deoxy-Hb respectively. The square with the number represent the 16 channels and the color of the square indicates the AOI in which the channel was included. Emitters are marked as E, while D indicates detectors. Areas underlying the channel are approximately over Brodmann's areas 10 and 46.

4 Discussion

In safety-critical environments such as piloting or air-traffic control, the study of mental overload is crucial to further reduce accident rates. However, researchers face the complexity of inducing an important amount of mental effort in the laboratory conditions. In this paper, we present a novel paradigm called Toulouse N-back Task (TNT) that combines the classical n-back task with a mathematical processing to replicate the multidimensional sustained high mental workload (MW) existing in many safety-critical occupations.

Twenty participants were tested with the TNT under three load factors (n = 0, 1, or 2) with fNIRS and pupillometric measurements to validate the effectiveness of the protocol. The results revealed that higher difficulty degraded the cognitive performance together with an increased bilateral PFC oxygenation (demonstrated by larger changes in oxy-Hb concentration) and an increase in pupil diameter. The variations in TNT difficulty successfully impacted behavioral without the need to reach high n-level (e.g., 3-back), that can provoke a disengaging of the task. Consequently, the TNT enables the progressive increase of the difficulty to generate a high and sustained mental load, for example, to test “high performer” individuals (airline pilots, air traffic controllers). The task also allows studying both tonic (during a block) and phasic (during mathematical processing) components of mental activity. This advantage of different time scale studies makes the task suitable for both tonic (such as brain oxygenation or tonic pupil diameter presented in this work) and phasic signal analysis (such as task-evoked pupillary response). Finally, the study confirmed that prefrontal oxygenation and pupil response are sensitive to variations in mental effort. For example, measurements of mental effort with fNIRS can help developing an effective design for future cockpit concepts.

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