Integrated view of the cognitive, cerebral and cardiac systems during an inhibition task

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INTRODUCTION

Maintaining optimal behavioral performance in dynamic, complex and stressful situations is a constant challenge. To better understand performance fluctuations and prevent accidents, it is important to have an integrated view of the cognitive, cerebral and cardiac systems that control behavior and physiological activity. However, these systems are traditionally studied separately despite their strong interdependence. Yet, a better understanding of the fundamental mechanisms of the integrated functioning of the central and peripheral nervous system should ultimately allow the development of new tools for promoting maximum cognitive performance and safety in natural situations, such as in civil or military aircraft. Regarding the cognitive system, a key cognitive function that allows adaptive behaviors and flexibility is inhibition. It sustains the ability to stop, avoid or ignore automatic, dominant or inappropriate responses in certain situations and to focus attention on relevant information (Miyake et al., 2000). Behavioral paradigms allow to examine inhibition ability such as in the flanker task (Ericksen & Ericksen, 1974) or the Go/No-Go task (Heil et al., 2000). Regarding the cerebral system, it is well known that specific brain networks are activated in order to support the processing of information during complex tasks. In particular when tasks involve inhibition, activated brain regions have notably been located in the cingulate, prefrontal, and parietal cortices (Collette et al. 2006). A technique for studying brain activity is functional near infrared spectroscopy (NIRS). It makes it possible to noninvasively monitor tissue oxygenation and hemodynamics of the brain, particularly by monitoring the variations of concentration in oxyhemoglobin and deoxyhemoglobin. This brain imaging technique has shown its interest in the evaluation of cerebral metabolic activity, in particular according to cognitive load in specific cortical regions (Fishburn et al., 2014). Finally, regarding the cardiovascular system, heart activity has been shown to adapt to levels of complexity of a cognitive task, presumably in order to support behavioral performance (Richter et al., 2008). Cardiac activity is known to be modulated by two branches of the autonomic nervous system (ANS): the parasympathetic branch has an inhibitory influence (decreases heart rate), while the sympathetic branch has an excitatory influence (increases heart rate) (Levy, 1990). Sympathetic activity can be accurately evaluated by calculating the cardiac pre-ejection period (PEP), which corresponds to the time interval between the onset of ventricular depolarization and the opening of the aortic valve (Bernston et al., 1994). While still relatively new in the field of cognitive neuroscience, PEP has been already used to study the relation between ANS activity and mental effort and has shown that it reduces as the task becomes more difficult (Richter et al., 2008; Silvestrini & Gendolla, 2013).

These three systems are thus essential to the adaptive capacities of the individual to face the demands of the environment. The link between inhibition and the cardiovascular system

(Kuipers et al., 2016) and the link between inhibition and the cerebral system (Herrmann et al., 2005) have been studied in the past but very few studies have examined the three systems altogether. Our understanding of their interactions or their integration into a functional system is therefore very limited. The aims of the present study are 1) to systematically examine the way these three systems react to a challenging task involving different levels of inhibitory control and 2) to examine whether they are functionally integrated to manage behavior adaptation.

METHODS

Participants

Thirty young adults (M_{age} = 20,23, ± = 2,36, 15 females) participated in the study and received a compensation of 10€. They reported no neurological or cardiovascular disorders. All participants had normal or corrected vision. They all gave their written consent at the beginning of the study, which was approved by the local ethics committee (IRB - N° 00011835-2021-0928-418).

Measures

Behavioral measures from the modified Flanker task

The behavioral task is a modified version of the Ericksen flanker task (Ericksen & Ericksen, 1974; Heil et al., 2000) involving neutral, congruent and incongruent conditions as well as conditions requiring a response (Go) or requiring not to respond (No-Go). The modified flanker task was presented on a computer screen and the participant responds by pressing one of the two keys on a response box. The task consists of responding as quickly and precisely as possible to a central stimulus, the target, by indicating the direction of the arrow (< or >) while ignoring stimuli placed on either side of the target (>> or << for the congruent and incongruent conditions or □□ for the neutral condition). The task was organized around three experimental blocks following training blocks. A first block, the neutral block, involving only neutral trials (e.g., □□<□□) corresponds to a choice reaction time task involving no or very little executive control. A second block, the flanker block, corresponds to the classical flanker task with congruent trials (e.g., <<<<<, 50%) and incongruent trials (e.g., <<><<, 50%). This condition makes it possible to assess interference management ability (inhibition of irrelevant information) by comparing performance on incongruent trials with that of congruent trials. A third block, the flanker no-go block, corresponds to the modified flanker task with additional Go trials (70%) and No-Go trials (30%) depending on the nature of a preparatory signal. Each trial is preceded by a preparatory signal (-----), which can be of the same color as the target (Go trial) or of a different color (No-Go trial). This condition makes it possible to evaluate the interference management ability, but also the response inhibition ability during No-Go trials requiring to stop (inhibit) the response normally expected. Thus, these three blocks differ in the amount of inhibitory control necessary for their successful execution. Each block lasted approximately 4 minutes 30 seconds and was repeated twice. The order of presentation of the blocks was counterbalanced between the participants. A 3-minute rest period was allowed between each block to ensure a return to the baseline level of cardiac activity (Czarnek et al., 2021). The dependent variables are percentage of correct responses and response time (RT) in ms for correct responses.

Cardiovascular measures

The measurement of cardiac activity was carried out using the Biopac MP160 system at an acquisition frequency of 2000 Hz. Once the training was finished, the electrocardiogram (ECG) and impedance cardiogram (ICG) electrodes were placed on neck and torso of the participant. Blood pressure (BP) measurements (Omron Carescape V100) were also recorded during each rest period in order to monitor BP evolution for the interpretation of ECG/ICG signals (Sherwood et al., 1990). The data collected were pre-processed on Matlab for ECG/ICG measurements using an in-house tool. PEP was calculated as the time interval between R-onset and B-point (Sherwood et al., 1990). R-onset is defined as the lowest deflection before R peak on the ECG signal. R-peaks were found using a threshold peak detection algorithm and visually inspected. The first derivative of the ICG signal was computed and the resulting dZ/dt signal was averaged over 1 minute epochs. B-point is located based on the RZ interval (Lozano et al., 2007). Resting PEP was calculated over the 3 minute rest period. To examine the dynamic of the cardiac activity during task blocks, mean PEP in ms was calculated on 4 successive windows of 1 minute. Dependent variables are mean PEP in ms and PEP reactivity in milliseconds (task PEP minus resting PEP).

Cerebral activity measures

Cerebral hemodynamics was monitored by near infrared spectroscopy using NIRScout system. A 16 sources and 14 detectors mapping was used, covering the orbitofrontal cortex, the dorsolateral prefrontal cortex, the inferior frontal gyrus, the supplementary and pre-motor area and parts of the parietal cortex. Eight short-channels were also used to remove systemic physiological activity. fNIRS data was processed using the BrainAnalyzIR toolbox (Santosa et al., 2018). First, the raw data signal was converted into optical density, then using the modified Beer-Lambert Law, optical density data was converted into oxyhemoglobin (HbO_2) and deoxyhemoglobin (HHb) concentrations. Then, a general linear model was used to process the data, using the autoregressive iteratively reweighted least squares (AR-IRLS) model, and using the short-channels data as regressors following the procedure recommended by Santosa et al. (2020). Dependent variables were beta values for HbO_2 and HHb.

Behavioral, ECG, ICG and NIRS data were synchronously recorded throughout the experiment to examine their concurrent evolution.

RESULTS

Data collection is still ongoing at the moment of submission of this abstract and thus not all results can be presented here. Only PEP and behavioral results will be presented and discussed.

Flanker task results

Overall, the percentage of correct responses was significantly more important in the neutral block (M = 99,52 ± 0,73) than in the flanker block (M = 98,07 ± 1,82), which was higher than in the flanker no-go block (M = 96,97 ± 1,83). Similarly, overall, RT significantly differed between the three blocks. RT were lower for the neutral block (M = 400,32 ± 58,24) comparing to the flanker block (M = 474,16 ± 69,18) and the flanker no-go block (M = 505,76 ± 82,82).
In the flanker block, mean RT of congruent trials (M = 413,11 ± 45,94) was significantly lower than mean RT of incongruent trials (M = 540,60 ± 97,36). Also, the percentage of

correct responses for congruent trials (M = 99,65 ± 1,34) was significantly higher than the one for incongruent trials (M = 92,63 ± 7,13). Similarly, in the flanker no-go block, mean RT of congruent trials (M = 440,95 ± 58,83) was significantly lower than the one of incongruent trials (M = 571,59 ± 120,96). Also, the percentage of correct responses for congruent trials (M = 99,49 ± 1,95) was significantly higher than the one for incongruent trials (M = 93,33 ± 8,01). Moreover, the percentage of correct responses for Go trials, the percentage of correctly answered trials, (M = 94,41 ±6,56) was significantly higher than the one for No-Go trials, percentage of correctly not answered trials, (M = 88,61 ± 13,55).

PEP results

For each task block, mean PEP of the first 1-min window was significantly lower than mean PEP for the 3 other windows, which did not differ each other. PEP was thus shorter during the first minute of the task and then rapidly went back to baseline value and stabilized at this level. Mean PEP during each resting block varied from 113,25ms to 115,04ms and mean PEP during each task block varied from 108,88ms to 114,95ms.

PEP reactivity calculated for the first 1-min windows of each blocks was significantly different from 0, indicating that task PEP was systematically lower than resting PEP during the first min of each task. After that, PEP reactivity was not different from 0, except for w3 and w4 of the flanker block which were significantly higher than 0. Comparison of the PEP reactivity of the first 1-min window for each block showed that while PEP reactivity for the flanker No-Go block was significantly lower than the one for the flanker block, PEP reactivity did not significantly differ between the flanker No-Go block and the neutral block or between the neutral block and the flanker block.

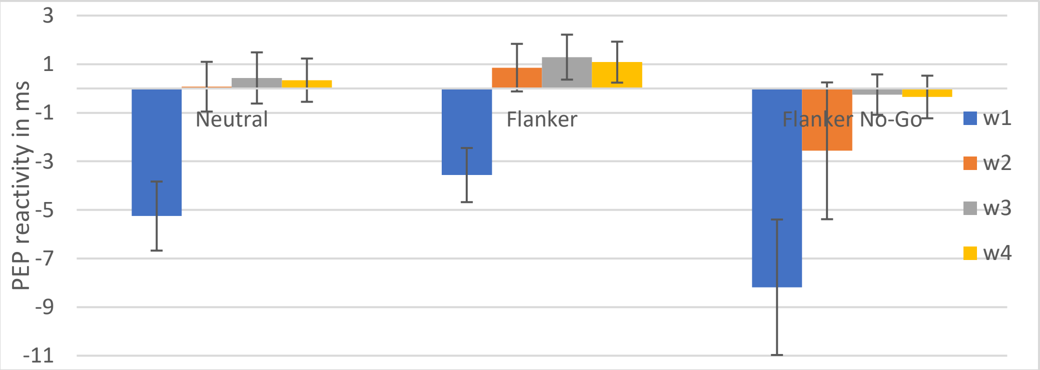

Figure 1: PEP reactivity (in ms) for each block and each 1-min window (w1, w2, w3 and w4) with standard error.

DISCUSSION

The preliminary results show that cognitive performance decreased with the increase of the amount of inhibition control required in the task and that PEP reactivity was significant for all block conditions, but only during the first minute. These results agree with past research but may highlight the rapid dynamic adaptation of the cardiac activity to task constraints. The flanker no-go block, which involves two kinds of inhibition (inhibition of irrelevant information and response inhibition), showed the most important PEP reactivity. This may reflect that the increase of inhibition control involved in the task required an increase of sympathetic activity to sustain effort and cognitive performance. However, contrary to what was expected, this effect on PEP reactivity was not linear as the flanker block had the lowest PEP reactivity. The next step is to analyze the cerebral hemodynamic data as a function of inhibition control requirement and ultimately to examine whether the variations in cardiac reactivity and cerebral activity during the cognitive tasks are functionally related and related to behavioral performance. If they were actually functionally connected, the integration of these dynamical cardiac and cerebral markers into an online control system could be used to detect and alert for performance and attention fluctuations in pilot activity.

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