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Sleep deprivation affects the sensitivity of proactive and reactive action monitoring: A behavioural and ERP analysis

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ABSTRACT

We studied the impact of sleep deprivation on action monitoring. Each participant performed a Simon task after a normal night of sleep and after 26 h of awakening. Reaction time (RT) distributions were analyzed and the sensitivity of the error negativity (Ne/Ne like) to response correctness was examined.

Results showed that (1) the Simon effect persisted for the longest RTs only after sleep deprivation and (2) the sensitivity of the Ne/Ne like to correctness decreased after sleep deprivation, especially on incongruent trials. This suggests that after sleep deprivation (1) the ability to inhibit prepotent response tendencies is impaired and (2) the sensitivity of a response monitoring system as revealed by the error negativity is less sensitive to performance.

In conclusion, action monitoring was affected by sleep deprivation as revealed by distributional analyses and the sensitivity of the Ne/Ne like to performance, which may be attributed to the fragility of prefrontal structures to sleep deprivation.

1. Introduction

Failing to respond correctly in a timely fashion to a stimulus, is a hallmark of sleep deprived state (Doran et al., 2001; Lim et al., 2008). Response accuracy under speed-stress may rely, at least in part, on "action monitoring" that is on the ability (i) to overcome prepotent response tendencies and (ii) to detect and correct errors. The "error negativity" (Ne) (Falkenstein et al., 1991) or "Error-Related Negativity" (ERN) (Gehring et al., 1993), an event-related potential starting just after electromyographic (EMG) onset and peaking just after mechanical error commission in reaction time (RT) tasks, is widely considered as an index of action monitoring (Holroyd et al., 2002). Different research groups (Hsieh et al., 2007; Murphy et al., 2006; Tsai et al., 2005) investigated the effect of sleep deprivation (SD) on the Ne. While Murphy et al. (2006) reported no effect of SD on Ne amplitude, both Tsai et al. (2005) and Hsieh et al. (2010) found that SD was associated with smaller Ne. The latter results suggest that SD impairs action monitoring. Therefore, both performance and EEG data converge in suggesting that SD impairs action monitoring.

Reaction Time Distribution and EMG patterns analyses under speed-stress allow to dissociate two complementary modes of action monitoring that contribute to response accuracy that will be respectively termed "reactive control" and "proactive control" in what follows.

1.1. Reactive control: detection and correction of errors

On numerous trials, the overt correct response is preceded by a covert incorrect response which can be evidenced by the presence of a subthreshold EMG burst associated with the incorrect response (Smid et al., 1990). These so-called "partial errors" are successfully suppressed, preventing a full performance error (Burle et al., 2002).

Thus, with respect to action monitoring, three categories of trials should be distinguished: full performance errors, partial errors, and "pure" correct trials. Partial error trials reflect the implementation of a reactive control that remedies errors before they turn into full performance errors.

Analysing the Laplacian transforms of EEG activity for all responses sorted as a function of the EMG pattern leading to correct, partial error and error responses showed that the Ne amplitude (Vidal et al., 2000, 2003) depends on the category of trial. The amplitude of the Ne is maximal for errors, minimal for correct responses and intermediate for partial errors. Such a gradation suggests that the negativities observed for the three types of responses reflect

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reactive control (Vidal et al., 2000, 2003). This notion is further supported by the fact that on one hand, the Ne-like is also sensitive to participant's performance (Allain et al., 2004) and that on the other hand, source analyses indicate that the Ne and Ne/like are generated by similar structures (Roger et al., 2010; Hoffmann and Falkenstein, 2010). A meta-analysis (Ridderinkhof et al., 2004a) indicates that the generator of the Ne is located within the Rostral Cingulate Zone which is known to be largely involved in cognitive control (Desmet et al., 2011). As the Ne starts just after EMG onset, it is likely that it reflects a reaction to correctness of the action monitoring system. As such, it can also be considered as an index of reactive control.

1.2. Proactive control: overcoming prepotent responses

Distribution analyses reveal that a proactive (i.e. preventive) control is implemented for correct trials in a behavioural paradigm known as the "Simon task".

This task, which is known to be particularly error- and partial error-prone (Craft and Simon, 1970; Hasbroucq et al., 1999, 2009; Burle et al., 2002), provides experimental contexts and theoretical models for analyzing proactive action monitoring when irrelevant external stimulus information elicits response impulses that interfere with goal-directed actions (Kornblum et al., 1990; Ridderinkhof, 2002; Van den Wildenberg et al., 2010). In the most common version of the Simon task (Hommel, 2011), the participants have to choose between a left- and a right-hand key press according to the colour of a visual stimulus presented a few degrees either to the left or the right of a fixation point. The performance expressed both in terms of error rate and RT is better when the required response corresponds spatially to the irrelevant stimulus location (congruent association) than when it does not correspond (incongruent association). This effect is termed the "Simon effect" (Hedge et al., 1975; Simon, 1990; Hommel, 2011).

A widely accepted interpretation of the Simon effect is that the irrelevant stimulus location automatically engages a response impulse in the spatially corresponding hand via a fast route while the relevant stimulus colour must be translated into the required response according to the task instructions via a slower controlled route (De Jong et al., 1994; Kornblum, 1994; Proctor et al., 1995).

When the stimulus-response association is congruent, the impulse triggered by the irrelevant stimulus location activates the required response, which facilitates response processing. In contrast, when the stimulus-response association is incongruent, the impulse triggered by the irrelevant location activates the non-required response which competes with the required one. This competition occurs at a cost and the performance is degraded.

RT distribution analyses reveal that the size of the Simon effect diminishes as RT increases (De Jong et al., 1994). In order to account for this effect, Ridderinkhof (2002) proposed the activation-suppression hypothesis according to which an active suppression mechanism of the fast route builds up over time. As this inhibitory mechanism is assumed to take time to develop, a reduction of the Simon effect appears with increasing RT. According to this view, faster responses should more likely be impulsive actions that are captured by the irrelevant stimulus dimension (Van den Wildenberg et al., 2010), via the fast route. Conversely, slower responses are less vulnerable to impulsive actions that are captured by the irrelevant stimulus dimension because selective suppression has time to build up and counteracts automatic impulses (Van den Wildenberg et al., 2010). Therefore, the active suppression of the fast automatic route, as revealed by the reduction of the Simon effect with increasing RTs, is assumed to represent a mechanism aimed at preventing the emission of incorrect activations when the required responses competes with the (non-required) automatically activated one (Ridderinkhof, 2002; Van den Wildenberg et al., 2010; Wylie et al., 2009). As this mechanism is aimed at avoiding the emission of prepotent incorrect activations, it can be considered as an action monitoring process. According to the activation-suppression hypothesis, the reduction of the Simon effect as RT increases manifests the implementation of an action monitoring process aimed at preventing the expression of EMG outputs associated to erroneous responses (partial errors and full performance errors, for a review see Van den Wildenberg et al., 2010). Since this process acts *before* the emission of any incorrect EMG activation, it can be considered as proactive (as opposed to the elicitation of the Ne, which occurs *after* incorrect EMG onset). To sum up, RT distribution analyses, because of their sensitivity to the fast route suppression, are efficient tools to explore proactive action monitoring and the impact of SD on these processes.

The first aim of the present study was to examine the effect of a 26 h SD on reactive and proactive control. In the event that this control is impaired, SD was expected to reduce the difference in Ne between the three response types: errors, partial errors and pure correct responses. In the event that proactive control is impaired, SD was expected to counteract the decrease of the Simon effect for long RTs.

2. Material and method

2.1. Participants

Six men and six women (mean age: 26; range: 21–37) volunteered in this experiment. They were all right-handed, no smokers and had a normal or a corrected to normal vision. Participants were nurses students at the Ecole du Personnel Paramédical des Armées de Toulon. They were paid 200 Euros for their participation. Informed written consent was obtained according to the declaration of Helsinki and the local ethics committee approved the experiment.

2.2. Task

The stimuli were digits 1, 2, 3, 4, 5, and 6 (2 cm height, 0.63° vertically) presented either to the right or the left of a central fixation point (a central cross 0.4 cm height and 0.4 cm width); the distance between the fixation point and each digit subtended 1.24° of visual angle. Half of the participants responded with the right thumb for even digits on the right button of a response pad (Neuroscan®) and with the left thumb on the left button for odd digits; the other half performed the reverse mapping. They were asked to respond as soon and as accurately as possible after the apparition of the stimulus. When the stimulus was presented on the same side as the correct response, the stimulus-response association was congruent. When the stimulus was presented on the side opposite to the correct response the stimulus-response association was incongruent. A block contained 50% of congruent trials and 50% of incongruent ones. A trial began with the presentation of a stimulus. Participants' responses turned off the stimulus and 500 ms later the next stimulus was presented. If participants had not responded 800 ms after stimulus onset, the stimulus was turned off and the next stimulus was displayed 500 ms later.

2.3. Design and procedure

Participants were comfortably seated in an armchair in a sound attenuated and air-conditioned Faraday cage. They faced a faradised screen on which the stimuli were presented. Participants were asked to maintain their gaze on the fixation point.

At the beginning of an experimental session, participants practiced one training block of 145 trials to reach a stable level of RT performance. Then, they were required to complete 16 blocks