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Electroencephalographic and skin temperature indices of vigilance and inhibitory control

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Neurophysiological markers of the ability to sustain attention and exert inhibitory control of inappropriate responses have usually relied on neuroimaging methods, which are not easily applicable to real-world settings. The current research tested the ability of electroencephalographic and skin temperature markers to predict performance during the Sustained Attention to Response Task (SART), which demands vigilance and inhibitory control. In Experiment 1, we recorded the electroencephalogram (EEG) during the performance of SART and found that event-related potentials underlying inhibitory control (N1 and N2/P3) were influenced by a time on task effect, suggesting a decrement in attentional resources necessary for optimal inhibitory control. In Experiments 2 and 3, we recorded skin temperatures (distal, proximal and the distal-proximal temperature gradient –DPG) and found that they were sensitive to differential demands of mental workload, and that they were related to behavioural performance in the SART. This study suggests that the recording of EEG and skin temperature may be used to monitor fluctuations of attention in natural settings, although further research should clarify the exact psychological interpretation of these physiological indices.

Vigilance refers to the ability to stay alert and focused on a task over time (Warm, Parasuraman, & Matthews, 2008). An important finding from vigilance research is that performance declines as time on task increases, known as the "vigilance decrement" (Davies & Parasuraman, 1982). The vigilance decrement was originally observed in classical vigilance tasks that demand sustaining attention for long periods of time (2 hours) in order to

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detect the occurrence of infrequent targets (Mackworth, 1948). Later studies have replicated this decrement in other vigilance tasks demanding response inhibition (Lara, Madrid, & Correa, 2014), such as the Sustained Attention to Response Task (SART; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997).

The SART is a go no-go task in which participants are to respond quickly to a sequence of digits from 1 to 9 randomly presented (go condition), but they have to withhold response when the digit "3" appears. This task has shown to be sensitive to impairments in executive functions related to inhibitory control in patients with frontal lesions (Robertson et al., 1997). The current research aimed to investigate physiological indices to predict human performance during vigilance tasks involving response inhibition, such as the SART.

A study recording Positron Emission Tomography (PET) while participants performed an auditory vigilance task (oddball detection) found decreasing activity over time on task in the right frontoparietal network and subcortical areas related to vigilance and arousal (Paus et al., 1997). Neuroimaging techniques usually require that individuals stay still within the scanner and are not appropriate for real-world settings. Therefore, alternative neuroimaging tools are increasingly used in neuroergonomics to study human performance in real life situations.

The recording of eletroencephalography (EEG) and Event-Related Potentials (ERPs) is a non-invasive and relatively portable method that can assess vigilance and sleepiness with high temporal resolution (Oken, Salinsky, & Elsas, 2006). ERP research on vigilance has reported that the P3 (a positive wave with parieto-central maximum amplitude within a latency range of 300-450 ms) shows amplitude decrements in parallel with declines in reaction time and detection accuracy over time in vigilance tasks (Koelega et al., 1992; Parasuraman, Warm, & See, 1998). The P3 has been related to attentional processing of task-relevant information and working memory operations. Its amplitude is interpreted as an index of the amount of resources allocated to the stimulus (Polich & Kok, 1995; Polich, 2007). When the task further demands response inhibition, a sequence of N2/P3 components (the N2/P3 complex) typically shows the largest amplitude over anterior brain regions (Bokura, Yamaguchi, & Kobayashi, 2001). The N2 is a negative potential with maximal amplitude at fronto-central sites and peak latency at around 200 ms. The N2 and P3 usually show larger amplitudes in the no-go relative to the go condition. Thus it is assumed that both reflect cognitive processes involved in response inhibition.

Both the N2 and P3 amplitude has been interpreted as neural markers of efficiency of inhibition. For example, studies using the Stop-signal task reported larger N2 amplitudes for successful versus failed inhibitions for the N2 (Luus, Van Snellenberg, & Liotti, 2007) and the P3 waves (Schmajuk, Liotti, Busse, & Woldorff, 2006). Moreover, it has been observed enhanced N2 amplitude in good relative to poor inhibitory performance in a go no-go task (Falkenstein, Hoormann, & Hohnbein, 1999). Likewise, it has been found that no-go P3 amplitude is attenuated in healthy participants with higher levels of impulsiveness compared to the low impulsiveness group in a hybrid flanker-go/no-go task (Ruchsow et al., 2008).

Only a few studies have focused on the ERP correlates of SART performance, reporting that N2/P3 amplitude was maximal to no-go stimuli (O´Connell et al., 2009; Zordan, Sarlo, & Stablum, 2008). Moreover, the N2/P3 complex was attenuated when individuals committed an error vs. a correct inhibition in no-go trials (O'Connell et al., 2009). Nevertheless, these studies did not address whether these potentials change as a function of time on task, which could be used to index the vigilance decrement. Therefore, the current research aimed to fill this gap in the literature.

On the other hand, skin temperature could be a promising candidate to predict task performance due to the recent development of low cost, wireless and easy-to-use portable devices that can reliably measure skin temperature under normal living conditions for several days (van Marken Lichtenbelt et al., 2006; Sarabia, Rol, Mendiola, & Madrid, 2008). However, to the best of our knowledge, skin temperature had not been recorded during the performance of a vigilance task demanding response inhibition.

In the present study, we tested whether physiological activity could predict fluctuations in the ability to control inappropriate responses during a long vigilance task. Skin temperature was recorded in three experiments, and electroencephalographic activity in Experiment 1, while participants performed the SART.

EXPERIMENT 1

Experiment 1 used a long version (83 minutes) of the SART to address the ERP changes associated with successful inhibitory performance as a function of time on task. We expected to replicate an accuracy decrement in response inhibition over time on task (Lara et al., 2014), concomitant with attenuated amplitudes of no-go N2/P3 potentials. We additionally tested whether the time on task effect was specific to late processing related to response selection and cognitive control (N2, P3), or it also influenced

stimulus processing at early perceptual stages, indexed by P1 and N1 potentials (peaking around 100 ms over posterior regions).

We also recorded distal skin temperature at the wrist during the SART. Increments in wrist temperature were correlated with slower responses in a perceptual discrimination task, thus suggesting its utility as a marker of vigilance (Romeijn & Van Someren, 2011). If so, we would expect a negative correlation between temperature and inhibitory performance in the SART.

METHODS

Participants. Nineteen undergraduate students from the University of Granada took part in Experiment 1. The inclusion criterion was having slept a minimum of 5 hours the night prior the experiment and having an intermediate chronotype (scores between 12-16 on the reduced scale of Morningness-Eveningness Questionnaire -rMEQ; Adan & Almirall, 1991). Our design therefore controlled for the effects of chronotype (i.e., internal preference for morning or evening times of day), as according to our previous research it influences the vigilance decrement (Lara et al., 2014).

Data from four participants with excessive noise in the EEG recordings and one participant who failed to follow task instructions were excluded from the analyses. Finally, the sample was constituted by 14 participants (mean age: 20 years, range: 18-32, SD: 3.81; 7 females). All participants reported normal or corrected-to-normal vision and no hystory of psychiatric and sleep disorders.

All participants signed a written consent form approved by the Ethics Committee of the University of Granada (Ref.:17/CEIH/2015). This study was conducted according to the ethical standards of the 1964 Declaration of Helsinki. After the experiment, participants were rewarded with course credits for their collaboration.

Apparatus and Stimulus. *Questionnaires.* Circadian typology was measured by the reduced scale of Morningness-Eveningness Questionnaire. The total score for the rMEQ and the MEQ showed a high correlation ($r = 0.898$, $p < 0.00001$; Adan & Almirall, 1991). Subjective activation and affect were assessed by a 0–100 visual-analog scale (Monk, 1989). The Attentional-Related Cognitive Errors Scale (ARCES; Cheyne, Carriere, & Smilek, 2006) measured susceptibility to cognitive errors in everyday life arising from lapses of attention. The Spanish version of the Mindful Attention Awareness Scale (MAAS; Soler et al., 2012) assessed attentional failures. ARCES and MAAS respectively correlate with the proportion of accurate inhibitions and RT (Cheyne et al., 2006). Trait impulsivity was measured by the adolescent

version of the Barratt Impulsivity Scale (BIS 11-A) translated to Spanish (Cosi, Vigil-Colet, Canals, & Lorenzo-Seva, 2008). These questionnaires shown good internal consistency (Cronbach α from .76 to .89).

Tasks. Programming, administration and behavioural data collection were controlled by E-prime software (Schneider, Eschman, & Zuccolotto, 2002) and run on an Intel Core 2 Duo personal computer with a 17" LCD monitor. EEG was recorded during the SART using EGI's Net Station software on a Macintosh computer with Power PC G5.

The *Psychomotor Vigilance Task* (PVT) is a 10-minute reaction time task that provides a measure of the overall level of participant's vigilance (Dinges & Powell, 1985; see Lara et al., 2014 for further details).

The *Sustained Attention to Response Task* (SART) requires participants to respond as quickly as possible to single digits randomly ranging between 1 and 9, unless the digit 3 was presented, to which they had to inhibit response (no-go trial). Stimuli appeared in white colour over a black background at the centre of the computer screen in one of five possible font sizes (48, 72, 94, 100 and 120 point, Times New Roman) that changed randomly on every trial (from 1.15º to 2.77º). A blank screen was presented for 50 ms followed by a digit that remained on the screen until the participant's response. If no response was made within 1200 ms, the next trial began. Each experimental block was composed of 200 go trials (5 font sizes x 8 digits x 5 trials) and 40 no-go trials (5 font sizes x 1 digit 6 x trials), leading to a no-go proportion of 0.17.

Two main modifications were made with respect to the original SART. First, instructions emphasized accurate response inhibition over fast responses. Digits turned red when the average correct response rate in no-go trials was below 0.71 (see Lara et al., 2014 for further details). Second, we lengthened the duration of the task (83 minutes) to test the time on task effect on performance and to obtain sufficient observations per condition in the EEG analyses. The task was composed of one practice block and 6 experimental blocks. Each experimental block lasted 13 minutes. Participants were informed about their mean RT and accuracy during obligatory one-minute rest intervals between blocks.

Skin temperature recording. Wrist temperature was measured using a temperature sensor (iButton- DS1921H; Maxim, Dallas), which has a temperature range from +15 °C to +46°C and 1°C of accuracy with a precision of 0.125 °C. A sensor was placed at the palmar side of the wrist of the non-dominant hand (with a sport band; see Sarabia et al., 2008, for a similar procedure). A second sensor recorded room temperature during the session. The sensors were programmed to sample every minute along the

experimental session. For technical reasons, one participant did not have temperature recordings and the sample for wrist temperature was composed of 13 participants.

EEG recording and preprocessing. EEG data were collected using a 128-channel Geodesic Sensor Net and the signal was amplified with a high-input impedance (200 MΩ) Net Amps (Electrical Geodesics Inc., -EGI-Eugene, Oregon; Tucker, Liotti, Potts, Russell, & Posner, 1994). Amplified analog voltages (filtered online at 0.1-100 Hz bandpass) were digitized at 250 Hz. Sensors were adjusted until impedances were less than 50 kΩ. The recording reference was the vertex channel.

Prior to ERPs analysis, we used independent component analysis (ICA) to identify and remove blink artifacts from filtered (1-40 Hz) EEG recordings. The mean number of components removed was 1.78 (range 1-5). Then, EEG data were segmented separately for each individual into stimulus-locked epochs using a time window ranging from -50 ms to 700 ms after the target onset in the no-go condition. Only ERPs for correct no-go trials (i.e. responses successfully inhibited) were analyzed. The epochs were grouped into 3 block conditions (blocks 1 + 2, blocks 3 + 4 and blocks 5 + 6, respectively) in order to obtain a larger number of segments per block and optimize the signal to noise ratio. The minimum number of epochs per condition for including a subject in the analysis was 30 artifact-free trials. Epochs were marked as bad if they contained ocular artefacts (electro-oculogram channel differences greater than 55 μV) or with more than 10 bad channels (voltage drifts of more than 70 μV in any channel). Single channels marked as bad were replaced using a spherical interpolation algorithm (Perrin, Pernier, Bertrand, & Echallier, 1989). Since the number of free-artifacts epochs was unequal across blocks, we randomly matched them to the minimum number of good epochs obtained in one of the 3 blocks in order to obtained comparable ERPs across conditions. The random selection of good epochs was carried out on the total number of valid trials per block after artifact detection, that is, epochs that contained artifacts were not included. These epochs were then averaged for each participant and condition (block) and referenced off-line to the average of all the channels. The epochs were baseline corrected for each subject using the 50 ms pre-stimulus period. Finally, we calculated grand average ERP waveforms for each condition by averaging across participants.

ERP analyses focused on the P1, N1, N2 and P3 potentials. According to previous literature, the visual inspection of the grand average waveforms and the voltage distribution over the scalp (topographic maps), we selected electrodes and time periods for analyses of amplitudes (see Figure 1).

Amplitude was calculated as the mean voltage in the time window symmetrically selected around the peak of interest.

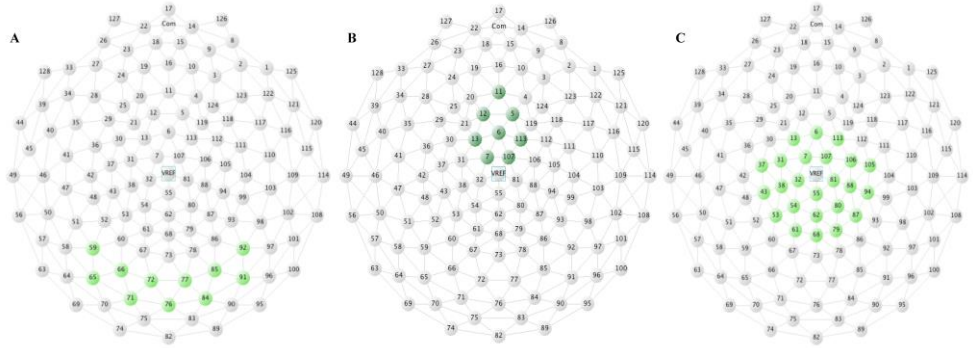

Figure 1. Network of electrodes used in the present experiment. The electrodes included in the analyses for P1, N1 (A), N2 (B) and P3 (C) are highlighted.

The P1 and N1 potentials were measured using a symmetric cluster of 11 electrodes (59, 65, 66, 71, 72, 76, 77, 84, 85, 91, and 92) over posterior sites. The temporal windows for determining the amplitude of both P1 and N1 were 89-141 ms and 217-273 ms, respectively. The N2 was analyzed over fronto-central electrodes (11, 12, 13, 5, 6, 7, 107, and 113) between 301 and 353 ms. The P3 had a broad scalp distribution and was measured over frontal-central-parietal regions (6, 7, 13, 31, 32, 37, 38, 43, 53, 54, 55, 61, 62, 68, 79, 80, 81, 87, 88, 94, 105, 106, 107, and 113) between 421 and 521 ms.

Procedure. Each participant completed a session of 2 hours and 45 minutes in an electrically isolated room. The session began at 11:00 h. The rMEQ was again administered at the moment of testing to confirm that participants had intermediate chronotype. First, temperature sensors were placed at the wrist to record a baseline of at least 30 minutes, during which participants completed the rMEQ, the ARCES, the MAAS, the BIS 11-A and the Monk's activation-affect scale. They also reported about sleep duration, psychiatric and sleep disorders and consumption of stimulants. Then, the PVT was administered. After the PVT, a sensor net was placed over the participant's scalp for EEG recording and participants performed the SART. Participants were instructed to respond with the dominant hand. Finally, they completed the Monk's scale again.

Design and statistical analysis. Temperature data were baseline corrected by subtracting the minute immediately preceding task onset from each of the 78 minutes of SART.

Subjective activation and mood states were analyzed using separate repeated measures analysis of variance (ANOVA) with Time (pre-test vs. post-test) as a within participants factor. Temperature data from each sensor, RT and accuracy performance in the SART and mean amplitude for each ERP component (P1, N1, N2, and P3) were also submitted to separate repeated measures ANOVAs with Block (1, 2, 3) as a within-subject factor. When the effect of Block was significant, planned comparisons were performed to test for differences between blocks (Block 1 vs Block 2 and Block 1 vs Block 3). In the SART, the RT analyses excluded trials with RT below 100 and above 1000 ms, and incorrect trials (i.e. responses in the no-go condition). The accuracy analysis computed the proportion of responses correctly inhibited to the no-go stimulus. All analyses excluded practice trials (i.e. trials from the practice block and five first trials of every experimental block, considered as warm-up trials). Simple linear correlations were calculated between self-reported questionnaires (MAAS and ARCES), performance on the PVT (mean RTs) and behavioral indices of the SART (mean RTs and accuracy). Correlation analyses between ERP measures and SART performance were also performed using the slope of the linear trend of data.

RESULTS

Demographic data. Information about group characteristics, mean room temperature and mean RTs on the PVT is detailed in Table 1.

Table 1. Mean and standard deviation (between brackets) for demographic data, mean RTs on the PVT and room temperature for the sample of Experiment 1.

Group characteristics	
Sample size	14
Age	20 (3.81)
Gender	7 females
Chronotype (rMEQ)	14.86 (3.11)
MAAS	4.16 (0.72)
ARCES (n=13)	29.85 (7.13)
BIS 11-A	66.07 (6.85)
Duration of sleep (in hours)	7.75 (1.19)
Wake time (in hours)	2.61(1.00)
PVT performance (ms) (n=12)	307.08 (25)
Room temperature (°C) (n=13)	22.22 (1.66)

Subjective activation and mood. The Time (pre-test vs. post-test) ANOVA on subjective activation showed a significant main effect, F (1, 13) = 23.37, p < .01, ηp^2= 0.64, with participants reporting higher subjective activation before (M: 61.07, SD: 4.39) than after the test (M: 34.07, SD: 4.37). The subjective affect analysis also showed a significant difference, F (1, 13) = 5.68, p = .03, ηp^2= 0.30, showing less positive affect after the test (M: 62.48, SD: 5.66) in comparison to pre-test assessment (M: 74.45, SD: 3.54).

Wrist temperature data. The ANOVA revealed a significant effect of Block on wrist temperature, F (2, 24) = 112.50, p < .01, ηp^2= 0.90, showing a decrease in wrist temperature from baseline over time on task (see Figure 2).

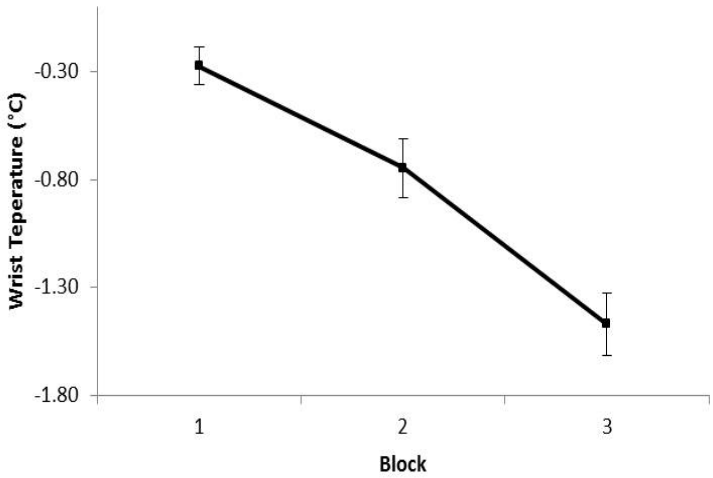

Figure 2. Decrement in wrist temperature (variation from baseline) as a function of time on task. Vertical bars denote +/- standard error of the mean.

Sustained Attention to Response Task (SART). The main effect of Block was not significant either on accuracy, F (2, 26) = 1.64, p = .21 (Figure 3), or reaction time (F < 1). The mean response latency was 392.51 ms (SD: 10.53) for Block 1, 398.52 ms (SD: 11.32) for Block 2, and 395.60 ms (SD: 10.70) for Block 3.

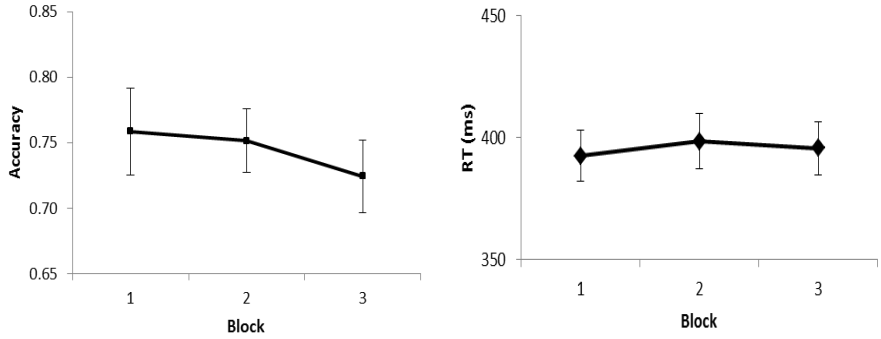

Figure 3. Mean proportion of accurately inhibited responses in the no-go condition and response times as a function of time on task. Vertical bars denote +/- standard error of the mean.

Event-related potentials The ANOVA on the N2 showed a significant effect of Block, F (2, 26) = 4.15, p = .03, ηp^2= 0.03, leading to amplitude decrements over time (Figure 4A). The N2 amplitude was larger in Block 1 (M: -1.00, SD: 0.49) than Block 2 (M: -0.53, SD: 0.39), F (1, 13) = 5.28, p = .04, and Block 3 (M: -0.27, SD: 0.53), F (1, 13) = 5.37, p = .04.

The P3 ANOVA revealed a significant main effect of Block, F (2, 26) = 7.81, p < .01, ηp^2= 0.37, with amplitude decrements over time (Figure 4B). In particular, Block 1 (M: 3.67 SD: 0.51) showed larger amplitude than Block 2 (M: 3.00, SD: 0.37), F (1, 13) = 8.71, p = .01, and Block 3 (M: 2.79, SD: 0.48), F (1, 13) = 9.20, p < .01.

The P1 mean amplitude did not differ significantly over time on task (p = .14). In N1 analyses, the main effect of Block was significant, F (2, 26) = 3.98, p = .03, ηp^2= 0.23, showing that N1 amplitude increased over time (Figure 4C). Planned comparisons showed the smallest amplitude in Block 1 (M: -2.08, SD: 0.45) relative to both Block 2 (M: -2.63, SD: 0.56), F (1, 13) = 5.24, p = .04, and Block 3 (M: -2.65, SD: 0.56), F (1, 13) = 4.71, p = .05.

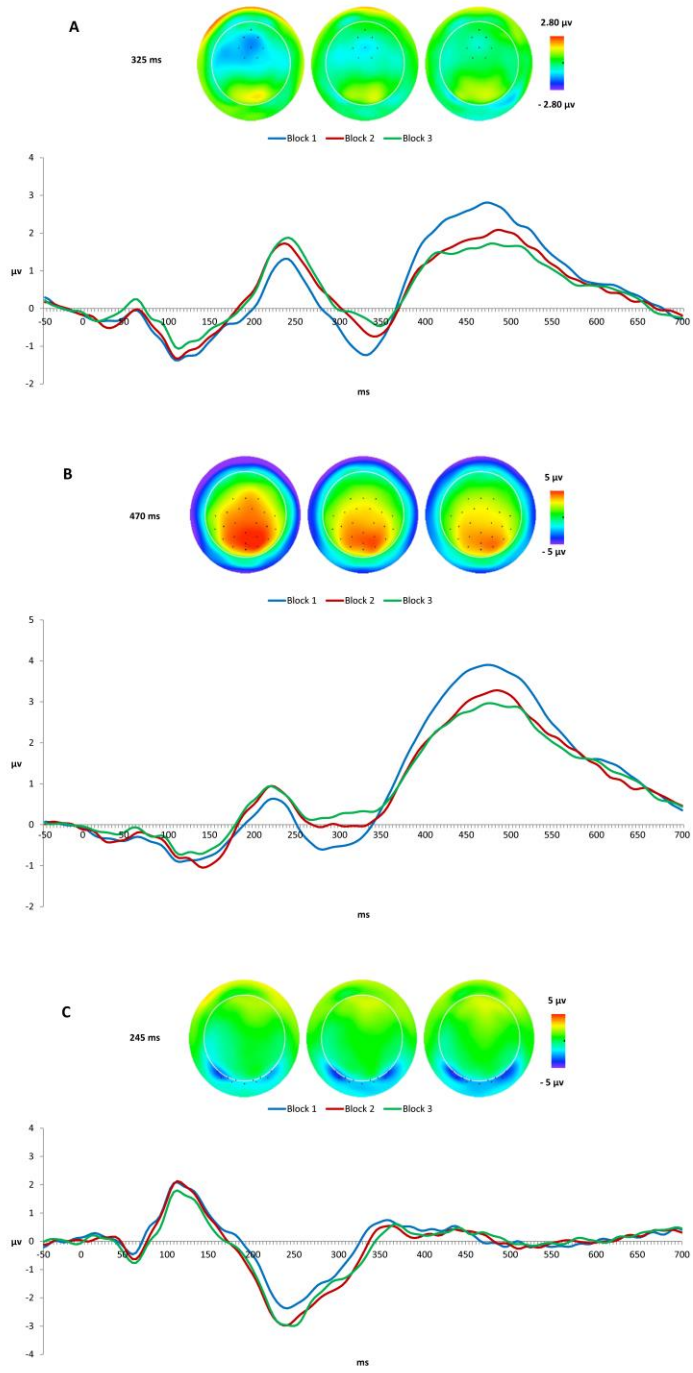

Figure 4. Grand average waveforms and topographies (with the corresponding electrodes used for the statistical analysis) of the N2 (A), P3 (B) and N1 (C) as a function of Block (Block 1: blue line, block 2: red line, block 3: green line).

Correlational analyses. The linear trend across blocks of ERP amplitudes did not show a significant association with inhibition performance on SART (all *ps* > .19). No significant correlations were found either between SART performance and self-report measures (all *ps* > .09) or between behavioural indices of the SART and RT performance in the PVT (p = .21).

DISCUSSION

The main aim of Experiment 1 was to explore electrophysiological markers of impaired inhibitory performance over time. Subjective reports confirmed that participants were vulnerable to the effect of time on task, as they reported both lower activation and more negative affect after the long vigilance task, but this decrement did not translate into behavioural performance significantly. Probably the sample size was insufficient (n = 14), since an analysis including participants with noisy recordings in the EEG (total n= 18) revealed marginal effects (p = .06), a result more consistent with our previous findings (Lara et al., 2014).

The ERP analyses on the no-go stimuli that were correctly inhibited showed that both N2 and P3 potentials decreased in amplitude, while the N1 increased amplitude along time on task. Previous research has found reduced P3 over time during a spatial go no-go task (Kato, Endo, & Kizuka, 2009), and reduced N2 and P3 were related to failures of inhibition in the SART (O'Connell et al., 2009). Our finding of amplitude decrements in N2/P3 with time on task might index a progressive depletion of attentional resources for inhibitory control, in line with the resource theory of the vigilance decrement (Grier et al., 2003; Parasuraman & Davies, 1977).

We further observed increased N1 amplitude along time on task. The N1 is considered to index perceptual discrimination (Vogel & Luck, 2000), and its amplitude in a go no-go task increases with task demands (by increasing time pressure to respond), presumably reflecting greater allocation of visual resources (Benikos, Johnstone, & Rooddenrys, 2013). Our finding of enhanced no-go N1 amplitude over time could thus reflect a greater difficulty for perceptual discrimination as time on task progresses. Recently, Haubert and colleagues (2018) has also found this unexpected result. They observed increased N1 amplitudes over time during a simulated radar task, followed by decreased P3 amplitudes. The N1 effect was interpreted as an increase in compensatory effort to remain attentive across time (Haubert et al., 2018). These authors, however, observed the increase of N1 amplitudes at a different scalp distribution (frontal and central sites), and therefore could reflect different neural or cognitive correlates.

The time on task effect could be also linked to several factors known to influence performance in vigilance tasks. Some ERP studies had shown how ERP amplitudes could be modulated by major factors to be considered in vigilance tasks. For instance, in an auditory oddball paradigm, the P3 amplitude increased after motivational instructions (Carrillo de la Peña & Cadaveira, 2000). Recently, Möckel and colleagues (2015) found increased response times, increased N2 amplitude and decreased P3 amplitude over time during a Simon task. The authors noted that the interactive effects of lower motivation to continue with the task, training or adaptation at the beginning of the task, and rest breaks could also account for the time on task effect, and not solely resource depletion due to time spent on task (Möckel, Beste, & Wascher, 2015). Accordingly, other possible interpretation may be in terms of a joint interaction between fatigue, motivation, and training effects, so future studies should investigate how these factors could modulate the time on task effect on inhibitory performance and inhibition-related potentials.

In spite of the absence of a parallel effect on performance, our current ERP results suggest that ERP measures could be a sensitive tool to assess changes in cognitive and perceptual processing associated to time on task. The ERP technique could provide additional and valuable information that is not directly observable at the behavioural level. For example, the ERP study carried out by Roche and colleagues (2005) showed that ERP measures could be useful to test individual differences despite the lack of differences at the behavioural level. In particular, they did not observe differences in performance between participants with high versus low proneness to lapses of attention in a go no-go task, but they found differences in the N2 and P3 components for correct relative to error waveforms (Roche, Garavan, Foxe, & O'Mara, 2005).

On the other hand, we expected to find a relationship between ERPs amplitudes and behavioural measures but we did not find any association. One possible explanation could be a non-linear relation. However, the lack of relationship between ERP amplitudes and behavioural measures could be explained by an inadequate statistical power due to the sample size.

Finally, wrist temperature declined over time on task, in line with a vigilance decrement. However, this result is generally observed during the morning hours of the circadian rhythm, where heat production exceeds heat loss, and temperature at distal skin regions normally decreases (Kräuchi, 2007a). Note that our participants were tested at 11:00. Therefore, Experiment 1 was not designed to clarify whether the decline in distal temperature was reflecting the natural circadian rhythm or a time on task

effect selectively caused by cognitive task demands. With this aim, we performed Experiment 2.

EXPERIMENT 2

Experiment 2 tested whether changes in skin temperature depend on task demands selectively by including a control condition (No Task group) where participants received the same sensory stimulation but did not perform the task (see Shaw et al., 2009, for a similar approach measuring transcranial Doppler sonography –TCD). The control group allowed measuring the change of skin temperatures without an active engagement in the cognitive task, therefore accounting for task unspecific changes produced by time-related effects of circadian rhythms. Participants were explicitly instructed to only look at the screen and not engage in any other activity (e.g. using the mobile phone) in order to ensure that they maintained visual attention passively.

In addition to distal temperature at the wrist, we recorded proximal temperature at the infraclavicular area and computed the distal to proximal gradient to compare which of these measures was sensitive to cognitive demands. Proximal temperature exhibits a similar time course as core body temperature, whereas distal temperature oscillates in opposite phase throughout the day. Core body temperature increases during daytime until it reaches its maximum (acrophase) at evening and then it continues to fall throughout the night. In contrast, distal skin temperature begins to rise at evening and reaches its acrophase during the sleep period (Kräuchi, 2007). In general, the moment when core temperature is at minimum, and distal temperature is at maximum (between 3 and 5 am), is associated with the lowest level of alertness as reported by subjects and indexed by reaction time tasks, such as the Psychomotor Vigilance Task (PVT; Wright, Hull, & Czeisler, 2002; Gradisar & Lack 2004).

Heat loss via distal skin regions promotes decrements in core body temperature, and is positively associated with high sleepiness and earlier sleep onset latency (Kräuchi, Cajochen, Werth, & Wirz-Justice, 1999). Heat loss is usually measured by the gradient between body temperature at proximal and distal skin sites (“distal to proximal gradient”, DPG).

Most studies had usually measured the course of vigilance and body temperature across the circadian cycle. As an exception, Romeijn and Van Someren (2011) studied fluctuations at a shorter time scale by using a 19-minute PVT where participants performed speeded perceptual discriminations and found that high proximal (infraclavicular) temperature

was associated with slower response times. The same relationship, albeit smaller than for proximal, was found for distal temperature and the gradient between skin temperatures. For example, they found that an increment in 1 ºC was related to slower responses by 27 ms. Therefore, these indices could be used as markers of the vigilance state at smaller time scales than the circadian rhythm, that is, during the performance of a cognitive task.

In Experiment 2 we tested for the first time whether skin temperatures could relate to inhibitory performance and whether they were selectively influenced by cognitive demands. We expected reduced vigilance and less correctly inhibited responses with higher skin temperatures (Romeijn & Van Someren, 2011).

METHODS

Participants. Twenty-three students from the University of Granada participated in Experiment 2. Participants were required to sleep for at least 5 hours the night prior to the experiment. One participant with hyperthyroidism and one taking antihistamines were excluded. The final sample included 21 participants, 10 randomly assigned to the Task Condition (all females) and 11 assigned to the No Task Condition (7 females; see Table 2 for further details). Participants reported no hystory of psychiatric and sleep disorders.

Apparatus and Stimulus. The questionnaires used in this study were the same as in Experiment 1. Differential demands between task conditions were checked by asking participants to rate their mental effort perceived during the test session using a visual analogue scale ranging from 0 (“little”) to 100 (“much”) on 4 items: strain, concentration, fatigue and motivation (Maire et al., 2014).

As in Experiment 1, we used the PVT and the SART (where they were informed about their mean RT and accuracy at the end of each experimental block during an obligatory rest interval of 30 seconds).

Skin temperature was monitored using temperature data loggers (Thermochron iButton- DS1921H, Maxim, Dallas; temperature range: +15 °C to +46 °C, with 1 °C of accuracy and a precision of 0.125 °C) as in Experiment 1. The sensors recorded one sample per minute. The wrist temperature sensor was placed at the palmar side of the non-dominant hand and attached with a sport band. Proximal temperature was recorded using a sensor fixed with adhesive tape to the infraclavicular skin region on the right chest. Two participants from the No Task condition reported unintentional removal of chest sensor and then their proximal temperature data were not

reliable and excluded from analyses (i.e. n= 9 for chest and DPG analyses). A third sensor recorded ambient room temperature.

Procedure. All participants completed a 2-hour session at 11:00 h under dim light conditions (< 8 lux). First, temperature sensors were placed at the wrist and infraclavicular area to record the 30-min baseline period, during which participants answered the mentioned health interview and questionnaires, and then they performed the PVT. Afterwards, participants assigned to the Task condition completed the SART while participants assigned to the No Task condition received the same sensorial stimulation but must remain as observers. Participants that performed the SART were instructed to respond with their dominant hand.

Design and statistical analysis. Separate one-way ANOVAs with Task Condition (Task, No Task) as a between subject factor were performed to test for differences in self-report scales (rMEQ, ARCES, MAAS, BIS 11-A), subjective effort, mean RTs on the PVT, room temperature and age. The PVT analysis excluded warm-up trials (first five trials) and RTs below 100 ms or above 1000 ms (3.10 % rejected). Scores on subjective activation and affect were analyzed using a mixed ANOVAs of 2 (Time: pre-test, post-test) x 2 (Task Condition: Task, No Task), with Time as a within-subject factor and Task as a between subject factor.

Skin temperature analyses were similar to Experiment 1. In addition, the DPG was calculated for each one-minute sample by subtracting proximal (infraclavicular area) from distal (wrist) temperature.

In the SART, the accuracy analysis computed the percentage of responses correctly inhibited to the no-go stimulus. Trials with RT either below 100 ms or above 1000 ms (2.60%) and incorrect trials (i.e. responses in the no-go condition) were excluded from the analysis. Both analyses excluded practice trials (i.e. trials from the practice block and five first trials of every experimental block considered as warm-up trials). The RTs were inversed transformed (1000/RT) before analyses and termed as response speed. Likewise, mean RTs in the PVT were analysed.

SART performance in the Task group as well as the group differences in skin temperatures over time on task were tested using non-parametric permutation tests (10000 times). Permutation tests are exact, unbiased and do not require meet parametric assumption requiring data fit the normal distribution (Ernst, 2004). Temperature data were analysed with Task Condition (Task, No Task) as between-subject factor and Block (Block 1, Block 2 and Block 3) as within-subject factor, while SART performance (speed and accuracy) from the Task group included the Block factor.

Significant main effects and interactions were explored by using post hoc and pairwise comparisons. 95% confidence intervals (CIs) are reported.

We further analysed the relationship between SART performance (accuracy and speed) and skin temperatures by linear mixed-effects analysis. Linear Mixed Models (LMMs) account for non-independence among the continuous observations from repeated measures designs and missing data. The model included Temperature and Minute as fixed effects factors. Intercepts for each subject and by subject slope were added as random effects. Reaction time data were inversed transformed (1000/RT) as we mentioned earlier, and as recommended for LMMs (Lo & Andrews, 2015). Permutation tests, CIs and mixed-effects models were performed using Matlab R2015b (MathWorks, Inc.).

RESULTS

Demographic data. Analyses confirmed that Task and No Task groups were matched in chronotype, age, impulsivity, attentional trait measured by MAAS, duration of sleep prior to the experiment and the wake time before the beginning of the experimental session (Table 2), except for ARCES scores, F (1, 19) = 5.69, p = .28, ηp^2 = 0.23, indicating higher susceptibility to lapses in the Task group (M: 34.5, SD: 1.45) than in the No Task group (M: 29.72, SD: 1.38). Information about RT performance in the PVT, room temperature, ingestion of food and consumption of stimulants for each group is detailed in Table 2.

Table 2. Mean and standard deviation (between brackets) for demographic data of Experiment 2.

	p- values	*Task Group*	*No Task Group*
Sample size		10	11
Gender		10 females	7 females
Age	.27	21 (1.01)	23 (0.96)
rMEQ	.84	13.67 (0.96)	13.40 (0.91)
MAAS	.77	4.41 (0.19)	4.33 (0.18)
ARCES	.03	34.50 (1.45)	29.73 (1.38)
BIS-11[a]	.64	63.40 (2.70)	61.64 (2.58)
Motivation (VAS)	.02	64.30 (7.95)	35.00 (7.95) [(3)]
Fatigue (VAS)	.59	72.20 (5.92)	67.60 (5.92)

Strain (VAS)	.40	37.30 (8.87)	48.00 (8.87)
Concentration (VAS)	.09	66.00 (8.48)	44.20 (8.48)
Duration of sleep (in hours)	.21	6.62 (0.36)	7.27 (0.35)
Wake time (in hours)	.31	2.85 (0.31)	2.41 (0.29)
RT performance in the PVT (ms)	.23	337.47 (6.44) [3]	326.61 (5.83)
Room temperature (baseline corrected)	.67	0.89 (0.05)	0.92 (0.05)
Ingestion of food		8 [1]	9 [2]
Coffee/Tea intake		5 [1]	4 [2]
Smokers		2 [1]	3 [2]

[1] For the Task group, 8 out 10 participants ate breakfast before session. Five participants reported caffeine consumption between one and a half and four hours before the experiment. Two participants smoked between half and one hour before the session.

[2] Nine participants ate breakfast before session and 4 of them reported caffeine consumption between one and two hours. Three participants smoked between half an hour and sixteen hours.

[3] One participant from the Task group did not have PVT data (n = 9). One participant from the No Task group did not complete correctly the VAS scales for effort (n = 10).

Self-report measures of activation and affect. The Task Condition (Task, No Task) x Time (pre-test, post-test) ANOVA showed a statistically significant difference between pre-test and post-test activation scores, F (1, 18) = 14.55, $p < .01$, $\eta p^2 = 0.45$. Participants reported higher subjective activation before (M: 53.84, SD: 2.65) than after the test (M: 39.87, SD: 4.07).The main effect of Task Condition ($p = .29$) and the interaction between Task Condition and Time ($F < 1$) did not reach significance.

Similarly, the analyses on affect scores showed a significant main effect of Time, F (1, 18) = 19.86, $p < .01$, $\eta p^2 = 0.52$, showing that participants reported less positive affect after (M: 59.96, SD: 3.18) than before the test (M: 75.82, SD: 3.54). The remaining effects did not reach significance ($Fs < 1$).

Regarding perceived effort, participants from the Task group reported higher motivation (M: 64.30, SD: 7.95) than the No Task (M: 35.00, SD: 7.95) during the test. The strain, fatigue and concentration scores did not show significant differences between groups (all $ps = .09$; see Table 2 for further details).

Behavioural Tasks. *Psychomotor Vigilance Task (PVT).* PVT performance did not differ between groups, F (1, 18) = 1.56, $p = .23$, suggesting that they were balanced in terms of their vigilance level before the test (Table 2).

Sustained Attention to Response Task (SART). The effect of Block on accuracy was significant ($p < .01$). Post hoc tests showed higher accuracy for

Block 1 with respect to both Block 2 ($p < .01$) and Block 3 ($p < .01$) but not between the last two blocks ($p = .47$; see Figure 5). The analysis of response speed showed a significant main effect of Block ($p < .01$), being faster in Block 2 than Block 1 ($p < .01$) and Block 3 ($p < .01$). There was no difference between Blocks 1 and 3 ($p = .55$; see Figure 5).

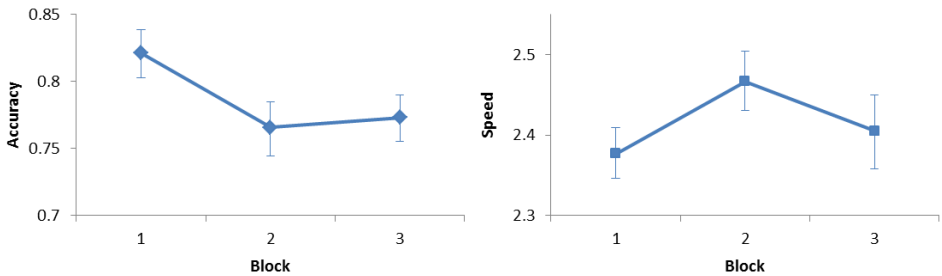

Figure 5. Accurate responses (proportion of correctly inhibited responses in the no-go condition) and speed (1000/Reaction Time) as a function of time on task in Experiment 2. Vertical bars denote 95% CIs of the mean.

Behavioural Tasks. Proximal temperature showed main effects of both Block and Task Condition ($ps < .01$; see Table 3). The Task group showed higher temperature than the No Task group (see Figure 6).

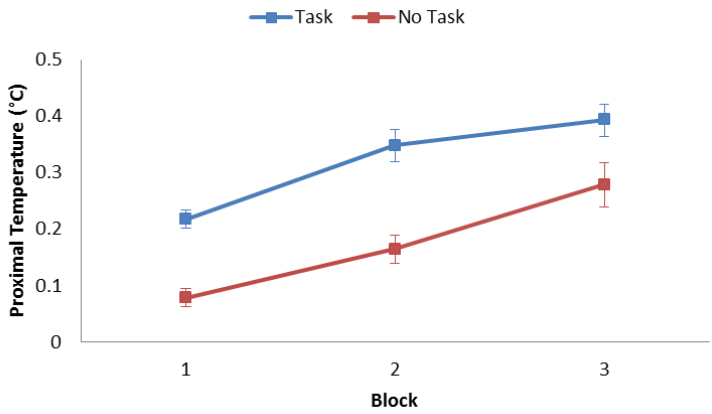

Figure 6. Proximal temperature over time as a function of Task condition in Experiment 2 (Task: blue line, No task: red line). Vertical bars denote 95% CIs of the mean.

The wrist temperature analyses showed a significant main effect of Block ($p < .01$). Post hoc tests revealed that temperature in Block 3 was lower

than in Block 2 and Block 1 (*ps* <.01, see Table 3). This was also true for DPG (all *ps* < .01). Moreover, DPG temperature was lower in Task vs No Task groups (*p* = .01, Table 3).

Table 3. Results of the permutation tests (p-values) and the mean temperature values [95% CIs] for both Task groups and each Block in Experiment 2.

	Distal (Wrist)	Proximal	DPG
Main effect of Task	p = .72	p < .01	p = .01
Task	0.004 [-0.04, 0.05]	0.32 [0.31, 0.33]	-0.31 [-0.36, -0.26]
No Task	0.02 [-0.03, 0.07]	0.17 [0.15, 0.19]	-0.22 [-0.29, -0.16]
Main effect of Block	p < .01	p < .01	p < .01
Block 1	0.14 [0.10, 0.17]	0.15 [0.14, 0.16]	-0.03 [-0.07, 0.005]
Block 2	0.12 [0.06, 0.18]	0.26 [0.24, 0.28]	-0.16 (-0.23, -0.10]
Block 3	-0.22 [-0.30, -0.15]	0.34 [0.32, 0.36]	-0.61 [-0.70, -0.53]
Interaction Task x Block	p = .80	p = .08	p = .76

Relationship between skin temperatures and SART performance. Linear mixed-effects model for accuracy and speed failed to show a significant effect of skin temperature (all *ps* > 0.13; see Table 4).

Table 4. Results of the linear mixed-effect analyses indicating effects of temperature variations as regressor for both responses correctly inhibited and speed of response per degree-Celsius change in temperature of Experiment 2. The regression model was: Behavioural index ~ 1 + Minute + Temperature + (1 + Minute + Temperature | Subject).

	Accuracy		Speed	
	Effect ± SE	**p**	**Effect ± SE**	**p**
Distal	0.106±0.06	0.13	-0.004±0.01	0.79
Proximal	-0.003±0.05	0.92	0.008±0.01	0.67
DPG	0.085±0.06	0.22	-0.005±0.01	0.74

DISCUSSION

Experiment 2 replicated the time on task effect on inhibitory control, such that participants' ability to inhibit inappropriate responses declined over time (Lara et al., 2014). Moreover, speed of response fluctuated over time on

task. Participants responded faster in the second half-hour of the task but then speed of response slowed during the last half-hour. In the SART, the go condition is expected to induce an automatic response tendency (Robertson et al., 1997). Therefore, speed of response increased in Block 2 in parallel to a decline in accurate inhibitory responses, suggesting that the automatic tendency to respond dominated over inhibitory control.

We further found that both proximal and DPG temperatures were sensitive to the task manipulation, as proximal was higher and DPG lower for the Task vs. No Task group. Moreover, the time on task effect was observed in all temperatures, with increments in proximal and decrements in wrist and DPG temperatures. However, this effect cannot be ascribed to a selective decrement of vigilance resources because it was observed in both task groups. Rather, this task unspecific effect fits well with the literature on circadian thermoregulatory processes showing that heat production exceeds body's heat loss during morning hours (Kräuchi, 2007a). Hence, it may be argued that the circadian rhythm exerted a strong influence on temperatures, thus masking a clear effect of cognitive demands.

In fact, subjective reports of activation, mood and perceived effort (fatigue, strain and concentration) did not differ significantly between task groups, suggesting that our manipulation of cognitive demands may have not been sufficiently robust. We only found a higher motivation in the Task group relative to the No Task group, a result that might be expected due to the Task group was encouraged to perform the task. It is possible that the control condition, where participants had to maintain visual attention passively without a challenge or task engagement for responding, was more demanding than we expected (Grier et al., 2003).

Therefore, Experiment 3 was designed to optimise the sensitivity of temperatures to differential task demands on the basis of two main changes: 1) we used a stronger and more precise manipulation of cognitive workload by using a dual-task methodology, and 2) we tested over different times of day to minimise the robust influence of circadian rhythms at a specific testing time, which would further enhance the generality of our findings.

EXPERIMENT 3

Experiment 3 tested whether distal, proximal and DPG temperatures were task-selective by asking participants to perform the SART simultaneously with a mental counting task. Skin temperatures were compared between the performances of single-task (SART) vs dual-task (SART and counting) conditions. We expected to find impaired inhibition

and larger vigilance decrement in the dual-task condition, as cognitive demands are higher when performing two concurrent tasks (Davies & Parasuraman, 1982).

Participants. Forty-two students from the University of Granada took part in Experiment 3 (26 females, mean age 21 years, SD: 2.54, range: 18-28). Inclusion criteria were similar to previous experiments.

Apparatus and Stimuli. All self-reported scales were the same as those used in Experiment 2 with the addition of the Pittsburgh Sleep Quality Index (PSQI; Royuela & Macías, 1997), which assessed subjective aspects of sleep quality.

Skin temperature measurements were recorded in the same manner as described in Experiment 2.

In Experiment 3, participants did not perform the PVT. On the other hand, we used a 55-min version of the SART. Participants completed one practice block and 4 experimental blocks (13 minutes each). Each trial began with the 100 ms presentation of a central fixation cross (yellow or blue-coloured) followed by a digit displayed for 1100 ms or until response (see Figure 7).

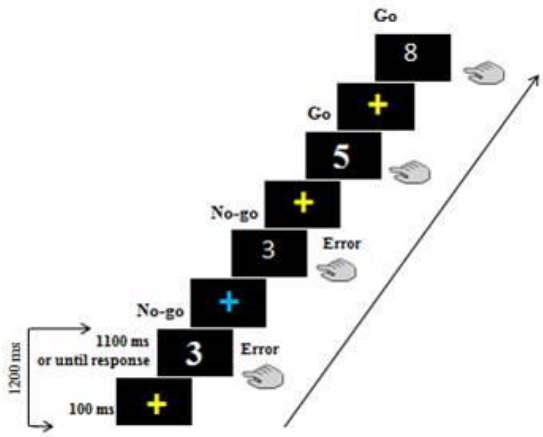

Figure 7. Sequence of events for both single-task and dual-task conditions in the SART.

Each colour was randomly presented and there was a low proportion of blue (ranging from 0.06 to 0.12 according to two different occurrence probabilities) in comparison to yellow crosses (from 0.94 to 0.87). The two probabilities of blue crosses were presented in alternating order across blocks and this sequence order was counterbalanced across subjects, so that half of

the participants first did a block with the low proportion of blue crosses and the other half a block with the high proportion. The crosses were presented with unequal probabilities to ensure that participants did not generate expectations about the occurrence of blue crosses across blocks.

In the dual-task condition, participants were instructed to perform the SART while at the same time they had to count and remember the number of blue fixation crosses. They reported the number of blue crosses presented when that block ended. At the end of each block, participants were informed about their mean RT, accuracy and the number of blue crosses presented during an obligatory one-minute rest interval. In the single-task condition, coloured crosses (blue and yellow) also appeared but participants performed only the SART. Since we used coloured crosses for the dual-task manipulation, in contrast to Experiment 2, the digit colour did not change to red to provide feedback online in this experiment.

Procedure. All participants carried out a 90-minute session twice, on two consecutive days, at the same time of day, with a lighting level of 97.9 lux. Experimental sessions were carried out at one of the following testing times: 9:00, 11:00, 13:00, 16:00, 18:00 or 20:00 h. The order of task condition (single, dual) was counterbalanced across participants. In one of the two sessions, they were asked to fill out the rMEQ and PSQI questionnaires while in the other they completed the MAAS, ARCES and BIS 11A scales. The Monk' scale activation and affect scales, the VAS scale for self-perceived effort, and questionnaires about sleep duration, time awaking, ingestion of food and consumption of stimulants were administered as in Experiment 2. Finally, participants performed the SART. They were instructed to complete the SART with their dominant hand.

Design and statistical analysis. Analyses were similar to Experiment 2, but measures of the secondary task performance were submitted to a repeated-measures ANOVA with Block (Block 1, Block 2) as within participant's factor (as in Experiment 2, blocks in the SART were collapsed: Block 1 + Block 2, Block 3 + Block 4, in order to obtain an appropriate number of observations per block for permutations tests). Responses in the counting task were recorded at the end of each block. We computed the percent deviation of responses with respect to the number of crosses presented in the block.

For skin temperature analyses, we performed a visual inspection of temperature plots to detect artifacts and noise during the recordings. In the chest temperature data, we observed changes equal to or greater than 0.5 °C from one minute to the next (similar to changes in skin temperature recordings of subject from Experiment 2 who reported unintentional removal of sensor). It is unlikely that such abrupt changes reflected physiological

fluctuations in skin temperature, so data from 6 participants were excluded from analyses. On the other hand, for technical reasons, one participant did not have wrist temperature recording and another participant did not have infraclavicular temperature recording. In addition, one participant reported he responded with the non-dominant hand and data were excluded from analyses on distal skin temperature to avoid influences on sensitivity to show temperature changes due to continuous motor responses required to perform the task. The final sample for wrist, infraclavicular and their gradient were constituted by 39, 35, and 34 participants, respectively.

Skin temperatures (distal, proximal and their gradient) and SART performance data from both single-task and dual-task conditions (accuracy and inverse transformed RTs –speed-) were analysed using non-parametric permutation tests as in Experiment 2 but with Task Condition (single, dual) as a within-subject factor. Likewise, LMMs were used to test the relationship between skin temperatures and SART performance.

RESULTS

Demographic data. Task conditions were matched in both duration of sleep ($F < 1$) and time awake ($p = .21$) before the test (further information in Table 5).

Table 5. Self-report measurements of Experiment 3

Mean (standard deviation) and scores range		
	Mean (SD)	***Range***
rMEQ	12.78 (3.28)	5-24
MAAS	4.03 (0.73)	1.73-5.73
ARCES (n=37)	36.11 (7.21)	26-54
BIS 11A (n=39)	65.41 (9.44)	41-85
PSQI (n=39)	8.05 (3.38)	3-19
Mean and standard deviation (between brackets) for single-task and dual-task conditions		
	p- values	***Single-task***	***Dual-task***
Activation pre-test (n=40)	.16	49.91 (2.33)	54.05 (2.55)
Activation post-test (n=40)	.94	41.11 (2.78)	41.29 (2.79)
Affect pre-test (n=40)	.91	71.88 (2.35)	72.13 (2.47)
Affect post-test (n=40)	.15	61.56 (2.42)	64.07 (2.61)
Motivation (VAS effort)	.09	58.42 (3.48)	63.37 (3.39)

Fatigue (VAS effort)	.82	63.87 (3.22)	64.70 (3.27)
Strain (VAS effort)	.10	47.10 (4.31)	53.25 (4.42)
Concentration (VAS effort)	.82	64.80 (2.79)	69.52 (3.39)
Duration of sleep (in hours)	.43	7.60 (0.22)	7.40 (0.17)
Wake time (in hours)	.21	5.17 (0.56)	5.61 (0.58)
Room temperature (baseline corrected)	.23	0.37 (008)	0.47 (0.02)
Ingestion of food		38 (1)	41 (2)
Coffee/Tea intake		22 (1)	21 (2)
Smokers		12 (1)	12 (2)

(1) For the single-task session, 38 out 42 participants ate breakfast before session. 22 participants reported caffeine consumption between half an hour and ten hours before the experiment. 12 participants smoked between one quarter of an hour and thirteen hour before the session.
(2) Forty-one participants ate breakfast before session and 21 of them reported caffeine consumption between half an hour and twenty hours. Twelve participants smoked between one quarter of an hour and fourteen hours.

Self-report measures of activation, affect and effort. The ANOVA on subjective activation showed a significant effect of Time, F (1, 39) = 14.07, $p < .01$, $\eta p^2 = 0.26$, with greater activation before (M: 51.98, SD: 2.80) than after the task (M: 41.20, SD: 3.52). Other effects did not reach significance (all *ps* > .27). Similarly, subjective affect was less positive after the test (M: 62.81, SD: 3.34) than before (M: 72.01, SD: 3.02), F (1, 39) = 29.65, $p < .01$, $\eta p^2 = 0.43$. Other effects were not significant (all *ps* > .30). Self-rating of effort did not differ between Task conditions (see Table 5 for further details).

Sustained Attention to Response Task (SART). The permutation test on accuracy revealed a significant main effect of Task ($p < .01$), showing higher accuracy in the single-task than in the dual-task condition. Neither the Block effect ($p = .38$) nor the Task x Block interaction ($p = .76$) reached significance.

The analyses on response speed showed significant main effects of Task and Block (*ps* < .01), with faster responses in single-task vs dual-task, and in Block 2 vs 1. The Task x Block interaction was significant ($p < .01$, Figure 8), leading to larger effects of Block effects in the dual-task ($p < .01$) vs single-task ($p = .01$).

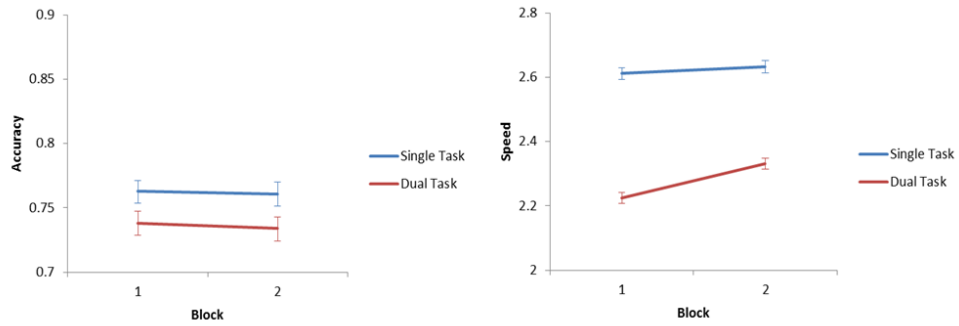

Figure 8. Accurate responses (proportion of correctly inhibited responses in the no-go condition) and speed (1000/Reaction Time) as a function of time on task in Experiment 3 (Single Task: blue line, Dual task: red line). Vertical bars denote CIs of the mean.

Skin Temperatures. Proximal (infraclavicular) temperature was higher in single-task vs. dual-task ($p < .01$), and higher in Block 2 vs. 1 ($p < .01$) (see Table 6 for further details). The Task x Block interaction ($p < .01$) showed that both tasks did not differ in Block 1 ($p = .11$) but they did so in Block 2 ($p < .01$; Figure 9).

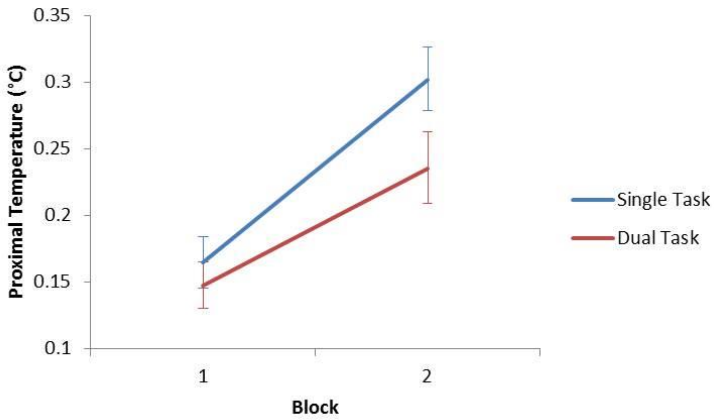

Figure 9. Temporal course of proximal temperature (baseline corrected) over time on task as a function of Task condition (Single Task: blue line, Dual task: red line). Vertical bars denote CIs of the mean.

Distal (wrist) temperature increased from Block 1 to Block 2 ($p < .01$), and was lower in single-task vs. dual-task. DPG temperature decreased from Block 1 to Block 2 ($p < .01$), and was lower in single-task vs. dual-task (Table 6).

Table 6. Results from the permutation tests (p-values) for main effects of Block and Task and their interaction. The mean temperature values and 95% CIs are provided

	Distal	Proximal	DPG
Main effect of Task	p < .01	p < .01	p < .01
Single task	0.09 [0.06, 0.12]	0.23 [0.22, 0.25]	-0.14 [-0.18, -0.10]
Dual task	0.18 [0.15, 0.21]	0.19 [0.17, 0.21]	-0.03 [-0.07, 0.004]
Main effect of Block	p < .01	p < 0.01	p < 0.01
Block 1	0.11 [0.09, 0.13]	0.16 [0.14, 0.17]	-0.05 [-0.08, -0.02]
Block 2	0.16 [0.12, 0.19]	0.27 [0.25, 0.29]	-0.12 [-0.18, -0.08]
Interaction Task x Block	p = .64	p < .01	p = .95

Relationship between skin temperatures and SART performance. Linear mixed-effects models for accuracy and speed revealed a relationship between both proximal and DPG temperatures and SART performance, mainly in the single-task condition. In the dual-task condition, only the DPG was associated with accuracy for response inhibition (Table 7).

Table 7. Results of the linear mixed-effect analyses indicating effects of temperature fluctuations as regressor for fluctuations in responses correctly inhibited and speed of response per degree-Celsius change in temperature. The regression model was: Behavioural index ~ 1 + Minute + Temperature + (1 + Minute + Temperature | Subject).

	Single task			
	Accuracy		**Speed**	
	Effect ± SE	**p**	**Effect ± SE**	**p**
Distal	-0.009±0.013	.46	-0.000±0.002	.78
Proximal	**0.069±0.016**	**<.001**	**-0.012±0.005**	**.05**
DPG	**-0.034±0.013**	**.01**	0.003±0.002	.25
	Dual task			
	Accuracy		**Speed**	
	Effect ± SE	**p**	**Effect ± SE**	**p**
Distal	-0.018 ± 0.015	.40	-0.004±0.004	.35
Proximal	0.022 ± 0.035	.56	-0.014±0.009	.15
DPG	**-0.034 ± 0.15**	**.03**	0.003±0.002	.88

DISCUSSION

Experiment 3 showed that inhibitory performance was affected by dual-task load, as reflected by lower accuracy and slower responses. Presumably, cognitive demands were higher and fewer resources were available for control when the SART was performed concurrently with the counting task, which required memory updating and therefore competed for executive resources (Miyake et al., 2000).

According to the resource theory, the vigilance decrement should be intensified in dual task (Helton & Russell, 2011). The dual-task would be more sensitive to detecting the vigilance decrement than the single-task, as it requires greater cognitive resources. However, we did not observe a time on task effect on accuracy in either single-task or dual-task conditions. In contrast, responses became faster over time on task, especially in dual-task, which could reflect the dominance of automatic over controlled response style. Alternatively, faster responses along blocks could reflect practice effects. As the secondary task gets practiced with time, this could be reflected as faster responses along blocks.

Skin temperatures responded consistently to our two main experimental manipulations. First, dual-task decreased proximal temperature and increased both wrist temperature and DPG. Second, time on task increased both proximal and wrist temperatures, but decreased the DPG.

In contrast to Experiment 2, linear-mixed effects analyses confirmed a relationship between performance and skin temperatures, probably for greater data variability due to test at different times of day and the larger sample size used in Experiment 3. Both DPG and proximal temperatures were associated with performance, while wrist temperature showed no relation. Specifically, increments in proximal temperature were related to higher accuracy for response inhibition and slower response speed (suggesting a controlled response set), but this result was only found in the single-task condition. Furthermore, increments in the DPG were related to lower accuracy for response inhibition both in single-task and dual-task conditions.

In sum, both proximal temperature and DPG could be reliable markers of the vigilance state. High proximal temperatures were related to better inhibitory control in the SART, while increments in cognitive demands by a dual-task decreased performance accuracy and temperature. The DPG showed the opposite pattern, such that high DPG was related to poor inhibitory control.

On the other hand, temperatures did not follow the expected pattern of a vigilance decrement, by which proximal temperature should have decreased over time (indicating lower vigilance state). However, time on task

increased proximal temperature. Again, this result might still reveal the influence of the circadian rhythm. Although we tried to minimise this effect by testing at different times of day, we should note that testing at night-time would have been ideal to fully compensate for circadian rhythm effects. That is, our finding of time on task effects on temperatures presumably reflected the overall circadian rhythm resulting from averaging morning and evening sessions, were proximal temperature generally increases and DPG decreases.

GENERAL DISCUSSION

Three experiments recorded electroencephalographical and skin temperature indices of vigilance and inhibitory control during SART performance. Previous research had related both the N2/P3 potential to SART inhibitory performance and skin temperatures to RTs in simple vigilance tasks. However, it remained to be addressed how these relationships evolve over time on task, and whether skin temperature could be generalised to index high-level cognitive processes, such as response inhibition demanded by the SART. Therefore, we were interested in how performance and physiological measures change as a function of time on task, in order to study and predict the vigilance decrement.

We found clear effects of time on task on both ERP and temperature measures, which were not so clear at the behavioural level. The P1 potential, related to early visual processing was not affected by time on task, but the N1 increased, and N2/P3 decremented over time. This finding suggests that attentional demands for correct visual discrimination (N1) increased over time, and that executive processing related to response selection and inhibition were less efficient along task performance. According to the resource theory of the vigilance decrement (Parasuraman & Davies, 1977), attentional resources are being depleted along the performance of demanding vigilance tasks, such as the SART. This increased demand over the less available resources was reflected at the neurophysiological level, but it did not translate into impaired behavioural performance. On the whole, our results may be interpreted as a decline in neural resources over time at the expense of maintaining successful, optimal performance. The cost of maintaining effortful processing was also manifested in subjectively experienced activation and mood. Indeed, we only observed a clear effect of time on task in Experiment 2, leading to lower accuracy and faster RTs, which suggested that automatic responding (fast but inaccurate responses) progressively dominated over the inhibitory controlled mode (slow but accurate responses) when participants performed the SART. However, this result was not clearly replicated in Experiments 1 and 3. It is possible that our

testing times did not optimise the observation of this result, as according to our previous research (Lara et al., 2014), the vigilance decrement in the SART was maximised when the participants were tested at suboptimal times of day according to their chronotype (i.e., 8 am for evening-type people and 8 pm for morning-type people). Here we tested intermediate chronotypes because they represent the 60% of the population, and at times of day (at 11 am in Experiments 1 and 2, and between 9 am and 8 pm in Experiment 3) that were not particularly suboptimal for them.

Accordingly, some practical implications could be derived. Time of day and chronotype effects should not be disregarded in research and clinical studies as well as real-world situations. Results from our current study and previous research (Lara et al., 2014) fit well with findings from studies in real-world settings. Overall, adolescent show time-of-day effects on attention and mood, with lowest levels in the early morning during the school day (Escribano & Díaz-Morales, 2014; Díaz-Morales, Escribano, & Jankowski, 2015). Moreover, academic achievement could be compromised if we considered chronotype, particularly for evening-type students (Goldstein, Hahn, Hasher, Wiprzycka, & Zelazo, 2007; Escribano & Díaz-Morales, 2016; Zerbini et al., 2017). Future research should take into account the neglected effects of both time of day and chronotype. In addition to time of day and chronotype effects on cognitive functions, many people experiencing a circadian misalignment due to imposed social schedules known as social jetlag (Wittmann, Dinich, Merrow, & Roenneberg, 2006). As shown some studies in the literature (Kelley, Lockley, Kelley, & Evans, 2017; Vetter, Fischer, Matera, & Roenneberg, 2015), adapting school and working schedules to chronotype could have a beneficial impact on cognitive and academic performance as well as health and wellbeing. Overall, our results are in line that negative effects of non-optimal schedules could be largely attenuated if we considered both time of day and individual differences in chronotype. Despite the current experiments were simplified and designed to control for the effect of time of day, we cannot rule out completely the strong influence of circadian rhythms in our data. In fact, our temperature measures, a classical marker of the circadian rhythm, showed consistent effects of time on task in all three experiments. Therefore, it is interesting to note that the typical use of long task periods when studying vigilance can be "contaminated" by circadian influences. However, to the best of our knowledge, our previous research (Correa, Molina, & Sanabria, 2014; Lara et al., 2014) and the current study are pioneers in highlighting this issue in vigilance research. On the basis of the standard designs in the literature, it is difficult to disentangle whether the time on task effect on neurobehavioural variables is due to either a task-selective decrement of resources (vigilance

decrement), to unspecific variations of arousal across the circadian cycle, or both. In this vein, we have already demonstrated an interaction between time of day and time on task in inhibitory performance (Lara et al., 2014), and others have reported variations of the P3 potential across time of day (Polich & Kok, 1995). Further research controlling for circadian rhythms (e.g., fully testing across the 24 h, or with forced desynchrony protocols) should clarify the task specific effects on neurobehavioural functions along the time of experimental sessions.

Although we acknowledge potential masking effects of circadian rhythms in time on task effects, our subjective measures indicated that the performance of a long vigilance task like the current SART had a robust impact in participants' psychological state (see also Rodríguez-Morilla, Madrid, Molina, & Correa, 2017). In all three experiments, participants reported being less active and in a more negative mood after completing the SART. This result is consistent with the view that vigilance requires cognitive effort and is stressful (Warm et al., 2008). Subjective feelings of mental exhaustion could be a natural consequence of the effort to maintain optimal performance over time, which might have precluded the observation of clear behavioural impairments in Experiments 1 and 3.

Our second main manipulation, based on cognitive task demands, revealed clearer findings than the effect of time on task. Both proximal and DPG temperatures were sensitive to variations in task demands in Experiments 2 and 3. In Experiment 3 we designed a more precise manipulation of cognitive load by comparing single-task vs. dual-task conditions in a within-subject design (rather than comparing task vs. no task groups), and found significant dual-task costs at both behavioural and physiological levels. When participants performed the SART simultaneously with the working memory task (mental counting), their accuracy to inhibit no-go stimuli was lower and their responses to go stimuli were slower, suggesting that both tasks competed for resources of inhibitory control. In this more demanding condition, proximal temperature was lower and DPG was higher, suggesting a lower level of arousal resources.

The results of the linear mixed-effects analyses of Experiment 3 were congruent with this relation between cognitive load and temperature. That is, an increment in proximal temperature was related to higher accuracy and slower response speed, suggesting a controlled task set, which was interfered under dual task conditions. Furthermore, an increment in the DPG was related to poor inhibitory performance, a relationship that was also convergent with the effects of dual tasking.

Our findings therefore extended those by Romeijn and Van Someren (2011), who reported a relationship between high temperatures and slower

response speed in a simple RT detection task. The authors suggest that DPG may index the vigilance state, as increased DPG has been related to higher somnolence (Kräuchi, 2007b), and therefore slower reaction times, which is congruent with our current findings. However, they did not discuss their counterintuitive finding of slower response speed with high proximal temperature. Both studies can be reconciled by assuming that high proximal temperature is related to higher arousal and a more controlled response set, which led to slower but more accurate responding in the SART. Unfortunately, the authors did not report accuracy in their task. Therefore, our research went beyond Romeijn's study by showing that both proximal temperature and DPG could predict RT performance, not only in simple RT tasks, but they can also predict accuracy in more complex tasks demanding inhibitory control.

The current study further indicated that wrist temperature could not predict SART performance reliably. Romeijn and Van Someren (2011) found that wrist temperature showed a smaller predictive power than proximal temperature. Motor responses might influence dynamics of skin blood flow, leading to changes from resting to continuous movement of the hand. Thus, proximal and DPG yielded more reliable results and could be used to predict inhibitory performance.

However, the functional significance of skin temperature indices requires further investigation. Given that an optimal level of arousal is necessary for proper vigilance and executive control (Robertson et al., 1997), a simple explanation to our finding is that variations in skin temperature may be coupled with fluctuations in arousal during task performance. States of optimal arousal as indexed by skin temperature could enhance vigilant attention and inhibitory control. In any case, the specific contribution of other psychological factors involved in the performance of vigilance tasks, such as stress (Warm et al., 2008), should be clarified in future research.

On the other hand, factors affecting circadian rhythms of temperature and vigilance performance should be taken into account and controlled by future studies. For example, body temperature is modulated by the menstrual cycle. Women had similar temperature rhythms to those observed in men before ovulation (follicular phase). After ovulation (luteal phase), core body temperature is about 0.4 °C higher than in the follicular phase, and the amplitude of the temperature rhythm tended to be reduced relative to the preovulatory period. On the other hand, women taking oral contraceptives show an elevated temperature during the follicular phase (Baker & Driver, 2007). In the same vein, gender could be an important factor to consider when measuring behavioural state of vigilance (see e.g. Blatter et al., 2006). Time since the last meal, stimulant consumption, medication, or individual

differences in personality such as extroversion-introversion could be also critically important (Ballard, 1996).

Similarly, the assessment of vigilance is affected by the length of sleep. In our study, we used as criterion sleep for at least 5 hours the night prior to the experiment, that can be considered as sleep restriction. However, inadequate amounts of sleep is quite common in our 24/7 society, and we considered that it is very interesting to investigate it because of is related to poor vigilance, increased attentional lapses and errors, and higher accident rates (Folkard, 1997; Goel, Rao, Durmer, & Dinges, 2009). In this regard, it should be pointed out that participants reported sleeping about 7 hours, as is recommended in order to favour optimal health (Watson et al., 2015).

To conclude, Experiment 1 followed an ERP methodology that has provided relevant electrophysiological markers underlying effective inhibitory control (N1 related to attention and visual discrimination between go and no-go stimuli, N2/P3 related to processes of response selection and inhibition). These inhibition-related potentials were influenced by the time on task effect, suggesting a vigilance decrement in attentional resources necessary for optimal inhibitory control. However, other interpretations of our results should not be discarded. Future work should replicate and also extend upon our findings. A challenge for future research is determine how major factors known to modulate vigilance contribute to the time on task effects by studies specifically designed for test or control their effect. In this regard, motivation may be especially important.

Experiments 2 and 3 performed skin temperature monitoring of vigilance in order to exploit the advantages of neuroergonomic methods (easy to use, non-invasive, wearable, comfortable, cheap and recording over long time periods) for being applied to field research. The current findings show for the first time that the recording of proximal and DPG temperatures is sensitive to variations in demands of mental workload and is related to the behavioural performance of tasks requiring vigilance and inhibitory control, such as the SART. Further research should address sensitivity and selectivity of skin temperatures to monitor attention fluctuations over periods shorter than 24h in natural settings and to clarify the functional interpretation of these indices.

RESUMEN

Índices de la vigilancia y el control inhibitorio basados en electroencefalografía y temperatura de la piel. Los marcadores neurofisiológicos de la habilidad para mantener la atención y ejercer un control inhibitorio sobre respuestas inapropiadas normalmente se han basado

en métodos de neuroimagen, los cuales no son fácilmente aplicables a entornos cotidianos fuera del laboratorio. La presente investigación evaluó la habilidad de marcadores electroencefalográficos y de temperatura de la piel para predecir la ejecución durante la tarea SART (Tarea de Atención Sostenida a la Respuesta), que demanda vigilancia y control inhibitorio. En el Experimento 1, registramos el electroencefalograma (EEG) durante la ejecución de la tarea SART y encontramos que los potenciales evocados relacionados con el control inhibitorio (N1 y N2/P3) fueron influenciados por un efecto de tiempo en tarea, sugiriendo un decremento en los recursos atencionales necesarios para un control inhibitorio óptimo. En los Experimentos 2 y 3, registramos tres marcadores basados en la temperatura de la piel (zonas distal, proximal y el gradiente proximal-distal –DPG) y encontramos que fueron sensibles a las demandas diferenciales de carga de trabajo mental, que además se relacionaban con la ejecución comportamental de la SART. Este estudio sugiere que el registro del EEG y de la temperatura de la piel se pueden usar para monitorizar fluctuaciones de la atención en contextos naturales, aunque investigación posterior debería proporcionar una interpretación psicológica más precisa de estos índices fisiológicos.

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