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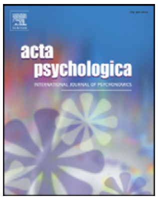

The effects of sleep deprivation on the attentional functions and vigilance

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ABSTRACT

The study of sleep deprivation is a fruitful area of research to increase our knowledge of cognitive functions and their neural basis. In the current work, 26 healthy young adults participated in a sleep deprivation study, in which the Attentional Networks Test for Interactions and Vigilance (ANTI-V) was performed at 10 a.m. after a night of normal sleep and again at 10 a.m. after 25.5–27.5 h of total sleep deprivation. The ANTI-V is an experimental task that provides measures of alerting, orienting and executive control attentional functions. Compared with previous versions, the ANTI-V includes a vigilance task, more reliable auditory alerting signals, non-predictive peripheral orienting cues, and also a neutral no-cue condition allowing the analysis of reorienting costs and orienting benefits. Thus, new evidence to evaluate the influence of sleep deprivation on attentional functioning is provided. Results revealed differences in both tonic and phasic alertness after sleep deprivation. Vigilance performance was deteriorated, while a warning tone was more helpful to increase participants' alertness, resulting in slightly faster RT and, in particular, fewer errors. The reorienting costs of having an invalid spatial cue were reduced after sleep loss. No sleep deprivation effect on the executive control measure was found in this study. Finally, since no control group was used, particular precautions were taken to reduce the influence of potential practice effects.

1. Introduction

The lack of proper sleep has a powerful detrimental effect on many everyday activities. Without a good night-time rest, people usually experience difficulties in, for example, performing effectively at work, carrying out habitual home duties or driving a vehicle safely. On the basis of these difficulties, it is frequent to find poorer cognitive functioning; including alterations in perception, attention, memory, executive functions, affective processing and others (see Killgore, 2010, for a review). As a consequence, the study of sleep deprivation (SD) is a fruitful area of research to increase our knowledge of cognitive functions and their neural basis. Also, a better understanding of SD would be useful in several applied areas, such as accident prevention, since lack of sleep is considered a major cause of road traffic accidents, especially at night or in professional drivers (Åkerstedt, Philip, Capelli, & Kecklund , 2011; Lal & Craig, 2001).

The influence of SD on attention has been studied frequently. Some researchers have even proposed that diminished vigilant attention is the basis of many other cognitive alterations usually found after sleep loss (Lim & Dinges, 2008). However, the evidence gathered for the different attentional functions has shown inconsistent results and many questions remain open (Killgore, 2010). Most of the studies addressing the effect of SD on attentional components used different experimental procedures or lacked an attention theory, which makes comparisons between them difficult. In the present study we take Posner and colleagues' neurocognitive model as theoretical background on attention and use a new version of the Attention Networks Test (ANT) that allows measurement of the different attention components in a single experiment. According to the model (Posner, 1994; Posner, 2008; Posner & Petersen, 1990), three different neural networks can be distinguished: alerting, orienting and executive control.

Abbreviations: ANT, Attention Networks Test; ANTI, Attention Networks Test for Interactions; ANTI-V, Attention Networks Test for Interactions and Vigilance; RT, Reaction Time; SD, Sleep Deprivation; SDT, Signal Detection Theory; St. Dev., Standard Deviation; VAS, Visual Analogue Scale for "Sleepy"; % errors, Percentage of errors.

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1.1. The alerting network

The alerting network is necessary to achieve (phasic alertness) and maintain (tonic alertness or vigilance) a state of high sensitivity to incoming stimuli. According to the literature (e.g., Killgore, 2010; Lim & Dinges, 2008), it is generally accepted that SD is a powerful way of reducing tonic alertness or vigilance. Regarding phasic alertness, the effect of sleep loss on this attentional function has been less frequently studied (see, for example, Cochran, Thorne, Penetar, & Newhouse, 1992; Sanders, Wijnen, & van Arkel, 1982). Recent evidence (Martella, Casagrande, & Lupiáñez, 2011; Trujillo, Kornguth, & Schnyer, 2009) has failed to find differences using the Attention Networks Test (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002) in a SD paradigm.

1.2. The orienting network

The orienting network is aimed at selecting information from the sensory input by allocating the attentional focus to a potentially relevant area or object in the visual field. A few studies have analysed the influence of sleep loss on attentional orienting but have produced contrasting results (Bocca & Denise, 2006; Casagrande, Martella, DiPace, Pirri, & Guadalupi, 2006; Martella et al., 2011; Trujillo et al., 2009; Versace, Cavallero, De Min Tona, Mozzato, & Stegagno, 2006).

To begin with, Casagrande et al. (2006) found a general de-arousal effect (a significant increase in reaction time, RT) across 24 h of SD, but not a selective effect on the orienting mechanisms. In contrast, Versace et al. (2006), using a partial sleep reduction paradigm, observed a significant slowing down of response time in the invalid condition (suggesting an impairment of the reorienting mechanisms), and consistent results were obtained by Bocca and Denise (2006) using the gap and overlap paradigms of saccadic eye movements.

It has been suggested (Martella et al., 2011) that one of the most relevant differences among the studies analysing the influence of sleep loss on attentional orienting concerns the type of manipulation used to measure attentional orienting. A sleep loss effect has been generally found when a peripheral predictive cue was presented (Martella et al., 2011; Versace et al., 2006), whereas it has not been usually observed by using central predictive cues (Casagrande et al., 2006). According to Martella et al. (2011), the main difference between these two types of task can be ascribed to some characteristics of the attentional processes involved: a central predictive cue produces a voluntary shifting of attention (Posner, 1980), while a peripheral predictive cue allows attentional orienting characterised by both automatic and voluntary processes (Jonides, 1981). Thus, one may assume that the low arousal due to SD affects the orienting mechanisms only when the task involves an automatic component of attention (Martella et al., 2011). However, some other studies have found results apparently contrasting to this suggestion. For example, Trujillo et al. (2009) performed a SD neurophysiological study, in which two versions of the ANT were compared, one using peripheral predictive cues and the other using central predictive cues. They concluded that a greater effect of SD is observed on endogenous (central) shifts of attention, as compared to exogenous (peripheral) orienting.

It can be proposed that previous results with spatial cues might be better explained in terms of peripheral (automatic) cueing compensating the deficits of SD due to reduced vigilance. For example, in Martella et al.'s (2011) study, a greater increase in RT was found in centre-cue trials than in those with a peripheral spatial cue, which were less affected by SD. In Versace et al. (2006) similar RTs were found in the valid peripheral cue condition with and without SD, whereas the participants' responses were slower after sleep loss in the invalid and neutral conditions (although in the latter the difference was not statistically significant). Additionally, Trujillo et al. (2009), using neurophysiological data, showed that the response to spatially cued targets in the exogenous task was preserved after SD, increasing the difference in amplitude of the N1 component with a peripheral spatial cue as compared to a neutral cue. On the other hand, this compensatory effect of the peripheral spatial cues might not take place when attention has to be oriented endogenously, probably because central resources are needed for endogenous orienting. Consequently, Casagrande et al. (2006), with central cues, observed a similar RT increment in each cue condition (valid, invalid, neutral) due to sleep loss. Also, Trujillo et al. (2009) found that the amplitude of the parietal N1 in response to both the neutrally cued and the spatially cued targets was similarly decreased by SD in the endogenous task.

1.3. The executive control network

The third network in Posner and colleagues' model of human attention is the executive control and involves the mechanisms for resolving cognitive conflict. According to Killgore (2010), inconsistent findings abound in the literature of the effects of SD on higher executive functions, and thus more studies are necessary to identify which components are more reliably altered. For instance, different studies failed to find a SD effect on interference using working memory tasks (Tucker, Whitney, Belenky, Hinson, & Van Dongen, 2010), the Stroop task (Cain, Silva, Chang, Ronda, & Duffy, 2011; Sagaspe et al., 2006) or the Simon task (Bratzke, Steinborn, Rolke, & Ulrich, 2012), whereas others reported a diminished performance (e.g., Stenuit & Kerkhofs, 2008). Also, when SD studies evaluated the executive network by using a flanker task, the impairment in conflict control was observed by some authors (Martella et al., 2011; Tsai, Young, Hsieh, & Lee, 2005) but not by others (Hsieh, Cheng, & Tsai, 2007; Murphy, Richard, Masaki, & Segalowitz, 2006).

It has been proposed that the inconsistent results on executive control networks could be ascribed to the high inter-subject variability of the effects of sleep loss (Banks & Dinges, 2007; Van Dongen, Baynard, Maislin, & Dinges, 2004). In line with this hypothesis, it was found that, after 48 h of SD, the deactivation of a neural network, including posterior cerebellum, right fusiform gyrus, precuneus, left lingual and inferior temporal gyri, was effective only in participants showing impairment in memory performance, but not in those able to maintain a higher performance (Bell-Mcginty et al., 2004). This variability in neural and behavioural responses to SD showing that greater activation of cortical areas during SD was associated with a better maintained performance, may account for many of these contrasting results.

1.4. The Attention Network Test for Interactions and Vigilance (ANTI-V)

In 2002, Fan and his collaborators developed the Attention Networks Test (ANT), a carefully designed computer task aimed at obtaining individual measures of alerting, orienting and executive control attentional functioning (Fan et al., 2002). The ANT is a combination of the cued reaction time (Posner, 1980) and the flanker task (Eriksen & Eriksen, 1974). According to the evidence gathered in different studies, the measures obtained from the ANT can be considered as usable indices of the three attentional networks, as found with behavioural data (Fan et al., 2002), in neuroimaging studies (Fan, McCandliss, Fossella, Flombaum, & Posner, 2005) and with the assessment of different metric properties (Ishigami & Klein, 2010). However, some potential limitations of the task were soon identified (Callejas, Lupiáñez, & Tudela, 2004). For example, the alerting and orienting effects were not assessed independently, as they were computed from the same factor manipulation. Also, exogenous and endogenous components of attentional orienting were confused, as the peripheral cue used was 100% predictable of the forthcoming appearance of the target stimulus. As a consequence, an improved variation of the task was proposed, known as the Attentional Network Test for Interactions or ANTI (Callejas et al., 2004). In the ANTI, an auditory warning signal was used, instead of a visual cue, to measure the alertness index independently, and non-predictive peripheral cues were presented to obtain the attentional orienting index.

Both the ANT and the ANTI have been successfully applied to assess attentional functioning in a great variety of research contexts, such as neurocognitive studies with normal children (Rueda et al., 2004), children with Attention Deficit Hyperactivity Disorder (Casagrande et al., 2011), dementia patients (Fernández et al., 2011; Fuentes et al., 2010), anxiety (Pacheco-Unguetti, Acosta, Callejas, & Lupiáñez, 2010) and even in the driver behaviour and traffic safety sphere (López-Ramón, Castro, Roca, Ledesma, & Lupiáñez, 2011; Weaver, Bédard, McAuliffe, & Parkkari, 2009). As a consequence, the tasks have been adapted to the different research contexts where they have been applied (for example, a lateralised version or LANT was developed to measure attention in both hemispheres; Greene et al., 2008). It is interesting to note that, in these tasks, alerting network functioning has generally been inferred from a phasic alertness measure, and the tonic alertness or vigilance level has been estimated indirectly (for example, by analysing the difference in RT between the first and the last block of the task, Ishigami & Klein, 2009; the overall RT across all correct trials, Martella et al., 2011, and Miró et al., 2011; or the overall RT only considering "no cue" trials, Posner, 2008). However, Roca, Castro, López-Ramón, and Lupiáñez (2011) have highlighted the importance of taking a direct measure of tonic alertness or vigilance while assessing the functioning of the three attentional networks. The indirect indices usually considered in the literature were only moderately associated with a direct measure of vigilance (i.e., the detection of an infrequent, unexpected and unpredictable stimulus embedded in an ANTI-based task). Thus, Roca et al. (2011) have proposed a new test, the Attention Network Test for Interactions and Vigilance or ANTI-V, as a new tool available for cognitive, clinical, or behavioural neuroscience research to obtain a measure of tonic alertness or vigilance, in addition to the usual phasic alertness, attentional orienting and executive control indices. As SD is usually associated with a reduction in arousal levels, the use of the ANTI-V in a SD study constitutes a unique opportunity to validate the vigilance index in the ANTI-V, in addition to the usual attention indices.

1.5. Objectives

The current study has two aims. First, as we mentioned above, we wanted to investigate whether the ANTI-V is actually measuring vigilance, and thus whether the vigilance indices calculated from this task are effectively influenced by sleep deprivation. This will provide further evidence of the validity of the ANTI-V, in addition to the original study by Roca et al. (2011). For example, it is expected that the percentage of hits and sensitivity will be reduced and the percentage of false alarms (or error commission) increased under SD. Regarding the response bias, previous evidence has generally found no change after sleep loss (Horne, Anderson, & Wilkinson, 1983). Besides, as found previously with the ANT and other attentional tasks (Casagrande et al., 2006; Killgore, 2010; Lim & Dinges, 2008; Martella et al., 2011), the participants' overall responses under SD should be slower and less accurate, RT variability will increase and a convergent SD effect is expected on other complementary vigilance measures, such as subjective sleepiness.

Second, the current study will provide further information about the influence of SD on attentional functioning. Although some previous studies have used the ANT in a SD paradigm, this is the first time that the ANTI-V, which provides rather different measures of alertness, attentional orienting and executive control, is being used in this context. Thus, different results may be expected as a consequence of the dissimilarities between these tasks.

For example, although previous studies using the ANT have failed to find a SD effect on phasic alertness (Martella et al., 2011; Trujillo et al., 2009), it is possible that this effect will be found using the ANTI-V. Phasic alertness is measured in the ANT using visual stimuli, while an auditory stimulus has been used in the ANTI-V. As claimed by Fan et al. (2002), auditory alerting cues often produce more automatic alerting than do visual cues and they might serve to aid the reliability of the alerting manipulation.

Regarding the attentional orienting score, the ANTI-V uses non-predictive peripheral cues. As a consequence, it is mainly exogenous orienting that is measured and the effect of SD on this attentional component will be more finely evaluated, in comparison with the ANT or other tasks using predictive peripheral cues, in which both exogenous and endogenous components of attention may be involved. To our knowledge, no other study has previously analysed the effect of sleep loss on an attentional networks test with non-predictive peripheral cues. Also, unlike the ANT, the ANTI-V includes valid and invalid cue trials, and therefore a separate cost and benefit analysis can be performed by comparing these trials with a neutral, no cue condition.

Finally, the ANTI-V is a more demanding task, since it requires a further vigilance component compared to the ANT or the ANTI, and it has been suggested that the need for cognitive control is increased to adequately distinguish the different types of stimuli (Roca et al., 2011). As a consequence, the increased cognitive control mechanism might partially compensate for the effects of SD on the executive control score, since previous evidence has shown that sleep deprived participants may perform better as tasks become more complex (see, for example, Baulk, Reyner, & Horne, 2001; Drummond, Brown, Salamat, & Gillin, 2004).

2. Material and methods

2.1. Participants

Thirty students from the University of Murcia participated in this study. Fourteen were males. Mean age was 21 (St. Dev. 2). The participants were selected as being right-handed and all of them reported normal or corrected to normal vision. Besides, they were all ignorant of the purpose of the experiment. At home, the participants were asked to complete a sleep questionnaire daily upon final awakening in the morning, for one week before the experimental session. Only those who reported normal sleep duration (7.5–8.5 h *per* day) and schedule (going to sleep at 11.30 p.m. ± 60 min and waking up at 7.30 a.m. ± 60 min) and who reported no sleep, medical, or psychiatric disorders, were included in the study. Moreover, participants were all non-smokers and were all drug-free. During the experimental session, the participants did not drink or eat anything containing caffeine (e.g., coffee, tea, chocolate). The experiment was conducted according to the ethical standards of the 1964 Declaration of Helsinki and was approved by the local ethical committee.

2.2. Apparatus

The experimental task was controlled by E-Prime v2.0 (Psychology Software Tools, Inc.) on a standard computer. The stimuli were presented on a 19 in. monitor and the responses were collected using a standard keyboard.

2.3. Stimuli and task procedure

The ANTI-Vigilance (ANTI-V) was used in the current study (Fig. 1). An extensive description of the task can be found in Roca et al. (2011). The following stimuli were presented: a black fixation cross, a warning tone, a black asterisk and a row of five cars pointing either left or right. The distance of the central target car was manipulated, being either centred or significantly displaced (i.e., appearing closer to one of the immediate flanker cars). Also, the vertical and horizontal location of each car was changed slightly in each trial, adding a random variability (± 4 pixels) to make it more difficult to distinguish between the centred and the displaced target car. The background was grey and a two-lane road with two parking lanes was represented in the centre of the screen. The target central car and its flankers appeared on one of the two parking lanes, above or below the fixation cross.

The instructions presented the task to the participants as a game, in which they were working in a Centre for Traffic Management and

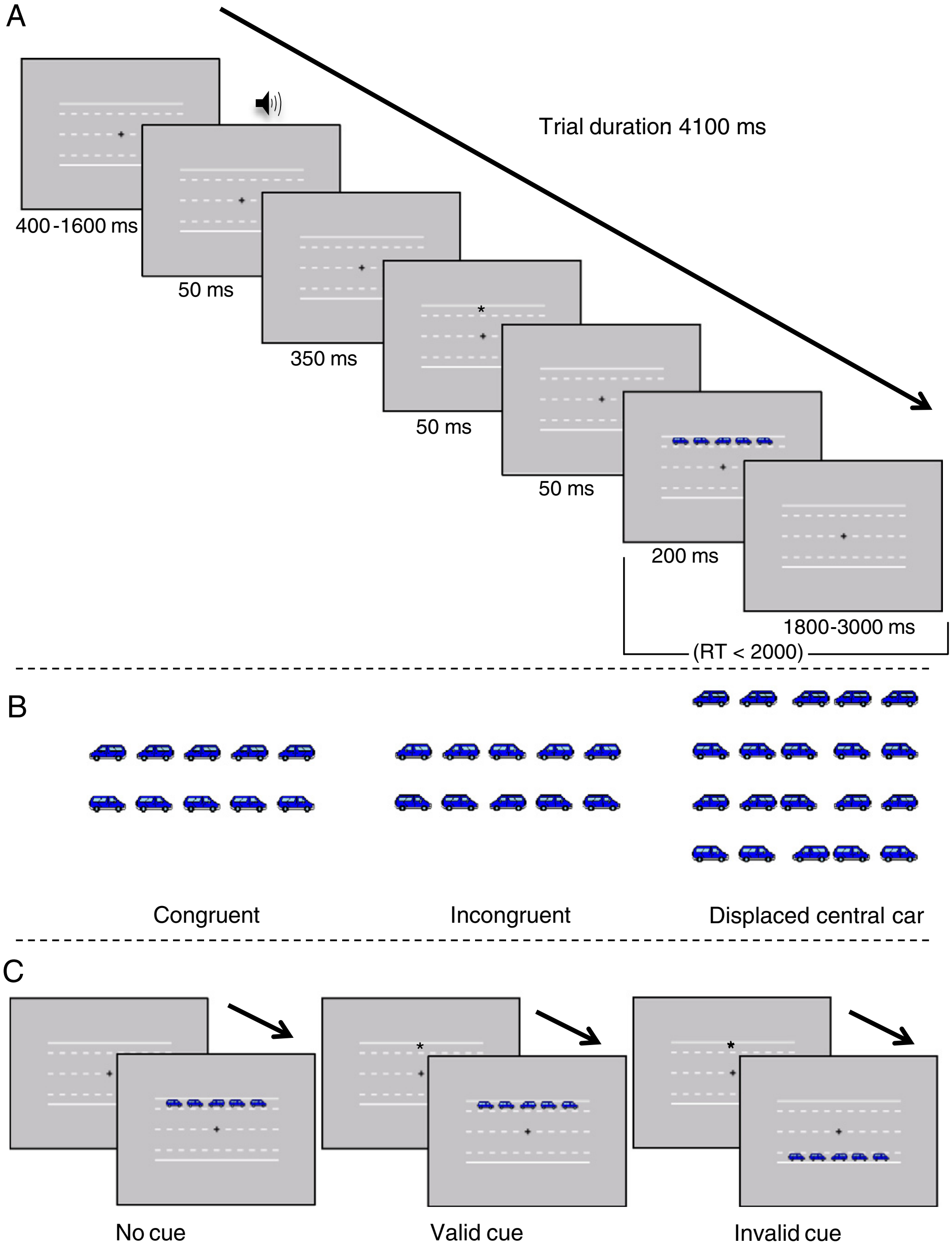

Fig. 1. Procedure and stimuli used in the Attention Network Test for Interactions and Vigilance (ANTI-V). (A) Schematic representation of the procedure. (B) The target stimuli. (C) The visual cue conditions.

studying the drivers' parking habits. The participants were presented for 200 ms with a row of five cars, above or below the fixation point. They had to indicate the direction of the central car, by pressing “c” (for left) or “m” (for right) on the keyboard. A period of 2000 ms was allowed for responses. The background road and the fixation point remained present until the end of the experiment. In every trial, the duration of the initial empty scene was randomly determined (400–1600 ms), and the duration of an identical final scene was adjusted so that the total trial time was 4100 ms.

In half the trials the flanker cars were pointing in the same direction as the central target car (congruent condition) and in the other half, in the opposite direction (incongruent condition). Also, 100 ms before the row of cars appeared, an asterisk was briefly presented (50 ms), either in the same location as the forthcoming target central car (valid visual cue condition), in the opposite location (invalid visual cue condition), or was preceded by no asterisk (no visual cue condition). These three visual cue conditions were equally probable. In addition, either a 50 ms auditory warning signal was presented 500 ms before the target car was shown (warning tone condition) or it was not presented (no warning tone condition). Finally, in 25% of the trials, the target central car was significantly displaced to the right or to the left. The participants were encouraged to identify these infrequent stimuli by pressing an alternative response key (spacebar) and ignoring the direction of the central car in these trials.

The task was composed of 8 blocks of 64 trials each (48 trials for the usual ANTI conditions and 16 vigilance trials with the displaced central target condition). In the first (practice) block, feedback on accuracy was provided. This first block was followed by a pause, and there were no more rest periods until the end of the task. In the second block, no feedback and no final pause were allowed, and thus nothing changed for the participants between the end of the second and the remaining blocks. Following Roca et al. (2011), the second block was not considered for further analyses, as the participants were still adjusting their performance to the requirements of the task. As a consequence, only the remaining 6 blocks were considered as experimental trials. The participants had to perform the task for more than 30 min, while completing the experiment required for around 40 min.

2.4. Complementary measures

We used a unidimensional Visual Analogue Scale (VAS) (Curcio, Casagrande, & Bertini, 2001) to evaluate subjective sleepiness. Participants were asked: "How do you feel right now with respect to the adjective *sleepy*?" They had to respond by making a stroke with a pen on a 100 mm long line. The stroke had to correspond with the point indicating the intensity of the self-evaluation. The VAS was anchored at one end with "not at all" (on the left) and at the other end with "very" (on the right). The distance of the mark from the left end of the line was considered as a dependent variable. In addition, the peripheral body temperature was measured, using a standard thermometer, to evaluate the participants' circadian rhythmicity.

2.5. Sleep deprivation procedure

The participants performed the experimental task on three consecutive days. First, an *initial experimental session* was scheduled on the afternoon (5–6 p.m.) previous to the sleep deprivation day, when the participants performed the ANTI-V task for the first time. The main objective of this initial experimental session was to reduce the impact of possible learning effects that may appear after a repeated presentation of the ANTI task (see Ishigami & Klein, 2010, and Section 5). Also, these data were used to evaluate whether the ANTI-V had been applied successfully and whether the main results by Roca et al. (2011) could be replicated. On the second day, after the participants had slept their usual time, they were received in the laboratory and kept awake for 28 h. During this time, they were asked to perform the ANTI-V at 10 a.m. (*without SD session*) again at 10 a.m. on the following day, after 25.5–27.5 h of total sleep deprivation (*with SD session*). The participants performed other cognitive tasks before and after completing the ANTI-V. In addition, subjective sleepiness (Visual Analogue Scale for "Sleepy") and corporal temperature were measured hourly from 9.00 a.m. on the second day to the end of the study. The participants had two breaks, one for lunch (about 2 p.m.) and one for dinner (about 10 p.m.). The experimenter continuously monitored the subjects, in order to avoid any naps.

2.6. Experimental design and data analysis

First, it should be noted that the initial experimental session, whose main aim was to reduce the impact of some potential learning effects and to replicate previous findings with the ANTI-V, was not directly comparable with the following two sessions (with and without SD), because the task was completed at different times of day and, thus, some circadian effects may also have arisen. As a consequence, data from the initial experimental session were analysed separately, by using a complete repeated-measures factorial design with the usual ANTI variables: 2 (Warning signal: No Tone/Tone) × 3 (Visual Cue: Invalid/No Cue/Valid) × 2 (Congruency: Congruent/Incongruent). Additionally, the location of the central target (Centred/Displaced) was manipulated to measure vigilance. Due to the infrequent presentation of the displaced central target and the fact that only a random selection of their combinations was used in the vigilance trials, this variable was not crossed orthogonally with the other three (warning signal, visual cue and congruency). Mean RT of correctly answered trials was inspected and values above or below two standard deviations were discarded (about 5% of trials). Twenty-six participants completed the task, although data from one of them was rejected from the analyses because the percentage of false alarms was unusually high (>3 St. Dev.) and the sensitivity was zero. A repeated-measures ANOVA with warning signal (no tone/tone), visual cue (invalid/no cue/valid) and congruency conditions (congruent/incongruent) was performed. The overall significance level was set at .05 and planned paired comparisons with the Bonferroni correction were performed when appropriate. If sphericity could not be assumed, degrees of freedom were adjusted using the Greenhouse–Geisser correction.

Regarding the SD study, a complete repeated-measures factorial design was used with the following variables: 2 (Session: With/Without SD) × 2 (Warning signal: No Tone/Tone) × 3 (Visual Cue: Invalid/No Cue/Valid) × 2 (Congruency: Congruent/Incongruent). Vigilance was manipulated in the same way as described in the initial experimental session. Mean RT of correct response trials was inspected and values above or below two standard deviations were discarded (about 5% of trials). Twenty-nine participants took part in the sleep-deprivation session, although the data from three of them were discarded because their percentage of errors was unusually high (>3 St. Dev.).[1] Mean correct RT and mean percentage of errors were then submitted to ANOVAs with session (with/without SD), warning signal (no tone/tone), visual cue (invalid/no cue/valid) and congruency conditions (congruent/incongruent) as repeated-measures factors.

Different attentional network scores were computed as a subtraction from specific average conditions: a) Phasic alertness score: no tone–tone conditions, considering only no-cue trials; b) Orienting score: invalid–valid conditions; c) Executive control score: incongruent–congruent conditions. Also, complementary cost and benefit indices were obtained from the visual cue conditions, in which the costs of presenting an invalid spatial cue were calculated as the difference between the average invalid trials minus no cue trials, and the benefits of having a valid spatial cue were computed as the difference between the no cue and valid trials. Regarding the vigilance task, the number of hits (proportion of correct spacebar responses to infrequent displaced targets) and false alarms (proportion of incorrect spacebar responses to frequent targets) were used to compute the sensitivity (d') and response bias (β), following the Signal Detection Theory (SDT) procedures. If hits of false alarms were 0 or 1, these values were substituted by .01 or .99, respectively, to obtain a suitable approximation to the SDT indices. Attentional networks scores and vigilance performance indices were submitted to ANOVAs with session (with/without SD) as a repeated-measures factor. Additionally, some global measures, such as overall RT, overall percentage of errors and overall St. Dev. of RT, were calculated separately for ANTI and vigilance subtasks and also submitted to similar ANOVAs.

3. Results

3.1. Initial experimental session

3.1.1. Reaction time

The analysis of RT data (Table 1) from the initial experimental session showed that the following main effects were statistically significant: warning signal ($F(1,24) = 13.51$; $p = .001$; $\eta^2 = .36$), visual cue ($F(2,48) = 43.67$; $p < .001$; $\eta^2 = .65$) and congruency ($F(1,24) = 118.97$; $p < .001$; $\eta^2 = .83$). Average RTs were faster when a warning tone had been presented (630 ms) than when it was absent (647 ms), and when the stimuli were congruent (612 ms) versus incongruent (664 ms). Planned comparisons of the visual cue factor revealed that average RTs were faster in valid trials (617 ms) than in invalid (656 ms) or no cue trials (641 ms), and also faster in no cue than invalid trials.

The Warning signal × Visual cue interaction was statistically significant ($F(2,48) = 4.30$; $p < .05$; $\eta^2 = .15$). However, no differences were found in the orienting score (i.e., invalid minus valid conditions)

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[1] Four participants failed to complete the initial experimental session. Data analyses were computed with and without these participants and results were approximate. Thus, the complete sample size has been used in the present paper.

Table 1
Mean correct reaction time, percentage of errors and standard deviations (between parentheses) in the initial experimental session. Warning signal (No tone/Tone), Visual cue (Invalid/No cue/Valid) and Congruency (Congruent/Incongruent) experimental conditions have been differentiated.

		Initial experimental session	
		No tone	Tone
Reaction time (ms)			
Invalid	Congruent	629 (79)	620 (83)
	Incongruent	689 (89)	687 (88)
No cue	Congruent	630 (72)	604 (75)
	Incongruent	681 (87)	648 (77)
Valid	Congruent	605 (74)	586 (87)
	Incongruent	646 (85)	632 (99)
Percentage of errors (%)			
Invalid	Congruent	3.2 (4.4)	1.5 (3.4)
	Incongruent	5.9 (5.6)	4.0 (4.9)
No cue	Congruent	2.9 (4.5)	2.0 (3.9)
	Incongruent	5.0 (6.3)	3.5 (4.6)
Valid	Congruent	2.5 (4.2)	2.6 (3.7)
	Incongruent	2.4 (3.7)	2.6 (4.2)

between the no tone (34 ms) and tone trials (45 ms) ($F(1,24)=2.01$, $p=.17$, $\eta^2=.08$). The Visual cue × Congruency interaction was significant ($F(2,48)=6.57$; $p<.01$; $\eta^2=.21$). Partial interactions showed that the congruency effect was higher in the invalid (64 ms) than in the no cue conditions (47 ms) ($F(1,24)=6.57$, $p<.05$, $\eta^2=.22$), while in the latter, the congruency effect was similar to the valid condition (44 ms) ($F(1,24)=.38$, $p=.54$, $\eta^2=.02$). The Warning signal × Congruency interaction was analysed by focusing only on the no cue condition to discard any influence of the cueing effect, and, as expected, it was non-significant ($F(1,24)=.37$; $p=.55$; $\eta^2=.02$). Finally, the second order interaction was not significant ($F(2,48)=.72$; $p=.49$; $\eta^2=.03$).

3.1.2. Accuracy

According to the analysis of the percentage of errors, the main effect of warning signal was statistically significant ($F(1,24)=5.27$; $p<.05$; $\eta^2=.18$), and the participants made more errors when the warning tone had not been presented (3.6%) than when it was presented (2.7%). The main effect of visual cue was statistically significant ($F(2,48)=3.61$; $p<.05$; $\eta^2=.13$). Planned comparisons with the Bonferroni correction failed to confirm any difference between the invalid (3.7%), no cue (3.3%) and valid conditions (2.5%), although values were in the direction expected. The main effect of congruency was also significant ($F(1,24)=6.22$; $p<.05$; $\eta^2=.21$), showing that participants made more errors in the incongruent (3.9%) than in the congruent condition (2.4%).

The Warning signal × Visual cue interaction approached significance level ($F(2,48)=2.83$; $p=.07$; $\eta^2=.11$). The Visual cue × Congruency interaction was significant ($F(2,48)=3.73$; $p<.05$; $\eta^2=.13$). As shown by partial interactions, the congruency effect was similar in the invalid (2.6%) and the no cue conditions (1.8%) ($F(1,24)=.58$, $p=.45$, $\eta^2=.02$), whereas in the latter, the congruency effect tended to be higher than in the valid condition (~0%) ($F(1,24)=3.49$, $p=.07$, $\eta^2=.12$). The Warning signal × Congruency interaction was not statistically significant ($F(1,24)=.26$; $p=.61$; $\eta^2=.01$). The second order interaction was not significant ($F(2,48)=.11$; $p=.90$; $\eta^2<.01$).

3.1.3. Attentional scores

Table 2 shows the attentional scores obtained in the initial experimental session, including the SDT-based measures for vigilance. Additionally, to evaluate whether the main results by Roca et al. (2011) could be found, correlations between the SDT vigilance measures and some other vigilance indices proposed for the ANTI (such as global RT or no tone and no cue RT) are reported in Table 3.

Table 2
Summary of main attentional measures in the initial experimental session. Mean and standard deviation (between parenthesis) are shown for: a) Attentional scores in reaction time (phasic alertness, orienting and executive control); b) Attentional scores in percentage of errors; c) Vigilance measures (Signal Detection Theory indices); and d) Global results (reaction time, percentage of errors and standard deviation of reaction time).

	Initial experimental session
a) Attentional scores: RT (ms)	
Phasic alertness	30 (31)
Orienting	39 (20)
Executive control	51 (24)
b) Attentional scores: % errors	
Phasic alertness	1.2 (3.4)
Orienting	1.1 (2.5)
Executive control	1.5 (2.9)
c) Vigilance measures (SDT)	
Hits (%)	55 (19)
False alarms (%)	2.8 (2.9)
Sensitivity (d')	2.1 (0.6)
Response bias (β)	8.4 (4.1)
d) Global results	
ANTI RT (ms)	638 (78)
ANTI % errors	3.2 (3.1)
ANTI St. Dev.	160 (44)
Vigilance RT (ms)	804 (100)
Vigilance St. Dev.	143 (48)

3.2. Sleep deprivation study

3.2.1. Reaction time

The analysis of RT data (Table 4) from the two SD conditions (with and without SD) showed that all main effects were statistically significant: Session ($F(1,25)=27.14$; $p<.001$; $\eta^2=.52$),warning signal ($F(1,25)=5.96$; $p<.05$; $\eta^2=.41$), visual cue ($F(2,50)=52.02$; $p<.001$; $\eta^2=.68$) and congruency ($F(1,25)=175.83$; $p<.001$; $\eta^2=.88$). Average RTs were faster after a normal sleep night (615 ms) than under SD (677 ms), when a warning tone had been sounded (640 ms) compared to when it was absent (652 ms), and when all the stimuli were congruent (619 ms) versus when they were incongruent (673 ms). Planned comparisons of the visual cue factor revealed that average reaction time was faster in valid trials (623 ms), than in invalid (660 ms) or no cue trials (655 ms).

The following interactions were statistically significant: Warning signal × Visual cue ($F(2,50)=11.77$; $p<.001$; $\eta^2=.32$) and Warning signal × Congruency ($F(1,25)=6.50$; $p<.05$; $\eta^2=.21$). First, following Callejas, Lupiáñez, Funes, and Tudela (2005), the Warning signal × Visual cue interaction was further analysed after removing no cue conditions, where no visual orienting could be measured. The interaction was significant ($F(1,25)=7.94$, $p<.01$, $\eta^2=.24$), suggesting that the cueing

Table 3
Correlations between the Signal Detection Theory vigilance measures and some other vigilance indices proposed for the ANTI.

	Hits	False alarms	Sensitivity (d')	Response bias (β)
ANTI RT	.53[**]	−.03	.44[*]	−.13
ANTI% errors	−.29	−.09	−.19	.14
NTNC RT	.48[*]	.03	.36[1]	−.16
NTNC % errors	−.31	−.10	−.20	.22

Note: ANTI RT = Average RT across all ANTI conditions (i.e., excluding vigilance trials); ANTI % errors = Average percentage of errors across all ANTI conditions; NTNC RT = Average RT of no tone and no cue ANTI conditions; NTNC % errors = Average percentage of errors of no tone and no cue ANTI conditions.

[1] $p<.10$.
[*] $p<.05$.
[**] $p<.01$.

Table 4
Mean correct reaction time, percentage of errors and standard deviations (between parentheses) in the two sleep deprivation (SD) conditions: Without SD and With SD. Warning signal (No tone/Tone), Visual cue (Invalid/No cue/Valid) and Congruency (Congruent/Incongruent) experimental conditions have been differentiated.

		Without SD		With SD	
		No tone	Tone	No tone	Tone
Reaction time (ms)					
Invalid	Congruent	604 (66)	596 (70)	660 (111)	659 (103)
	Incongruent	659 (71)	671 (81)	710 (77)	722 (103)
No cue	Congruent	619 (64)	580 (63)	676 (91)	645 (104)
	Incongruent	659 (75)	628 (65)	717 (89)	713 (116)
Valid	Congruent	578 (65)	554 (69)	632 (89)	629 (96)
	Incongruent	627 (78)	609 (82)	677 (88)	678 (116)
Percentage of errors (%)					
Invalid	Congruent	1.1 (2.5)	0.8 (2)	15.3 (12.6)	8.0 (9.1)
	Incongruent	4.4 (6.2)	3.3 (4.2)	22.6 (19.2)	13.1 (12.6)
No cue	Congruent	1.0 (1.8)	0.6 (1.5)	14.8 (12.2)	10.7 (11.9)
	Incongruent	3.0 (3.6)	1.8 (4)	18.3 (15)	12.2 (10.3)
Valid	Congruent	1.9 (2.7)	0.7 (2)	15.2 (13.3)	8.5 (8.7)
	Incongruent	2.3 (3.4)	2.1 (4.1)	15.5 (11.3)	10.5 (10.7)

effect was greater for the tone (45 ms) than for the no-tone (30 ms) conditions. Second, the Warning signal × Congruency interaction was analysed by focusing only on the no-cue condition, to discard any influence of the cueing effect, and this was also significant ($F(1,25) = 4.99$, $p < .05$, $\eta^2 = .17$). Further analyses revealed that the congruency effect was higher when a warning tone had been presented (58 ms) than when the tone was absent (41 ms). As this interaction was unexpected (it is usually non-significant with the ANTI-V task), separate analyses were carried out for the without SD session ($F(125) = 1.40$, $p = .25$, $\eta^2 = .05$) and the SD session ($F(1,25) = 3.36$, $p = .08$, $\eta^2 = .12$), suggesting that the interaction effect may be unreliable (it was not significant in the separate analyses) and, possibly, was only present in the SD session (where an unconfirmed tendency was observed). Regarding the Visual cue × Congruency interaction, this was close to reaching statistical significance ($F(2,50) = 2.60$; $p = .08$; $\eta^2 = .09$). In relation to the SD effects, the interaction between Session and Warning signal was statistically significant ($F(1,25) = 6.13$, $p < .05$, $\eta^2 = .20$). Further analyses revealed that the phasic alertness effect was smaller in the SD session (17 ms) than in the without SD session (35 ms) (see Fig. 2). No other interaction was found to be statistically significant (neither approached, all $p > .10$).

Finally, an additional cost and benefit analysis was performed on the visual cue variable, showing that the costs were absent under SD (~0 ms) as compared to without SD (11 ms) ($F(1,25) = 6.02$; $p = .02$; $\eta^2 = .19$), whereas the difference in benefits was not statistically significant (34 ms vs. 30 ms, respectively) ($F(1,25) = .60$; $p = .45$; $\eta^2 = .02$).

3.2.2. Accuracy

The average percentage of errors was analysed and all main effects were also statistically significant: Session ($F(1,25) = 37.40$; $p < .001$; $\eta^2 = .60$), warning signal ($F(1,25) = 40.82$; $p < .001$; $\eta^2 = .62$), visual cue ($F(2,50) = 4.33$; $p < .05$; $\eta^2 = .15$) and congruency ($F(1,25) = 13.46$; $p = .001$; $\eta^2 = .35$). On average the participants made more errors when they were under SD (13.7%) than after a normal sleep night (1.9%), when the warning tone was absent (9.6%) than when it had been presented (6.0%) and when distracters were incongruent (9.1%) versus when they were congruent (6.5%). Planned comparison of the visual cue factor showed that the percentage of errors was smaller in the valid trials (7.1%) than in invalid trials (8.6%). No cue trials (7.8%) were not found to differ significantly from valid or invalid trials.

The interaction between Visual Cue and Congruency factors was statistically significant ($F(2,50) = 7.42$; $p < .01$; $\eta^2 = .23$). As shown by partial interactions, the congruency effect was higher in the invalid condition (4.5%) than in the no cue condition (2.1%) ($F(1,25) = 7.78$; $p < .01$; $\eta^2 = .24$), whereas the latter was similar to the valid condition (1.0%) ($F(1,25) = 1.56$; $p = .22$; $\eta^2 = .06$). In addition, the interaction between Session and Warning signal factors was statistically significant ($F(1,25) = 12.07$; $p < .01$; $\eta^2 = .33$). Further analyses revealed that the phasic alertness effect was higher in the SD session (5.2%) than in the without SD session (0.72%) (see Fig. 2). No other interaction was found to be significant.

Finally, the cost and benefit analysis on the visual cue variable did not reveal any statistically significant difference in the percentage of errors. The costs were similar with and without SD (<1%) ($F(1,25) < .01$; $p = .96$; $\eta^2 < .01$) and the benefits were slightly higher after sleep loss (2% vs. ~0%), although this difference was not statistically significant ($F(1,25) = 2.82$; $p = .11$; $\eta^2 = .10$).

3.2.3. Attentional scores

Table 5 and Fig. 3 summarise attentional scores with and without SD. Results and significance tests are identical to the Session interaction effects presented above and are therefore omitted here. In relation to the vigilance performance indices, the percentage of hits was lower under SD (45%) than after a normal sleep night (57%) ($F(1,25) = 23.71$; $p < .001$; $\eta^2 = .49$) and the sensitivity-d′ was also lower with SD (1.9) than without SD (2.3) ($F(1.25) = 24.11$; $p < .001$; $\eta^2 = .49$). The differences in the percentage of false alarms ($F(1,25) = 2.78$; $p = .11$; $\eta^2 = .10$) and the response bias ($F(1,25) = 1.74$; $p = .20$; $\eta^2 = .07$) were not statistically significant in this study. Additionally, the global differences in Vigilance RT ($F(1,25) = 23.48$; $p < .001$; $\eta^2 = .48$) and Vigilance St. Dev. of RT ($F(1,25) = 7.42$; $p < .05$; $\eta^2 = .23$) were statistically significant. Under SD, participants were slower (864 ms vs. 775 ms) and their variability was higher (195 vs. 157 ms) compared to the without SD session. Also, the differences in global St. Dev. (of RT) for the ANTI subtask was also found to be statistically significant ($F(1,25) = 32.09$; $p < .001$; $\eta^2 = .56$), suggesting that the variability was higher after SD (217 ms) than without SD (148 ms). Results and significance tests for global ANTI RT and for global ANTI % errors are identical to the Session main effects presented above and are therefore also omitted here.

3.2.4. Change in sensitivity (d′)

An additional analysis was performed to provide further evidence supporting that the differences reported in phasic alertness and reorienting costs indices were effectively associated with the tonic alertness reduction. The change in sensitivity (d′) between the two sessions (With SD minus Without SD) was introduced as a covariate and the differences in attentional scores were compared in separate ANCOVAs. After introducing the covariate, neither the differences in phasic alertness scores in RT ($F(1,24) = 0.77$; $p = .39$; $\eta^2 = .03$) or in percentage of errors ($F(1,24) = 2.82$; $p = .11$; $\eta^2 = .11$), neither the differences in reorienting costs ($F(1,24) = 0.40$; $p = .54$; $\eta^2 = .02$) were statistically significant. This suggests that the significant differences previously reported were mainly related to the change in tonic alertness between the sleep deprivation conditions.

3.2.5. Complementary measures

Finally, subjective sleepiness (Visual Analogue Scale for “Sleepy” or VAS) and corporal temperature measures are shown in Fig. 4. VAS hourly scores were submitted to a repeated-measures ANOVA and significant overall differences were found ($F(27,675) = 25.14$; $p < .001$; $\eta^2 = .50$). A planned trend analysis revealed a strong lineal component ($F(1,25) = 149.94$; $p < .001$; $\eta^2 = .86$), suggesting a clear increase in subjective sleepiness over time. The average VAS score in the morning (9–12) after SD was significantly higher than the morning after a normal sleep night ($F(1,25) = 55.37$; $p < .001$; $\eta^2 = .69$).

Regarding the participants' corporal temperature, an expected circadian rhythmicity was found with minimum values around 6 a.m. The repeated-measures ANOVA revealed significant differences in the

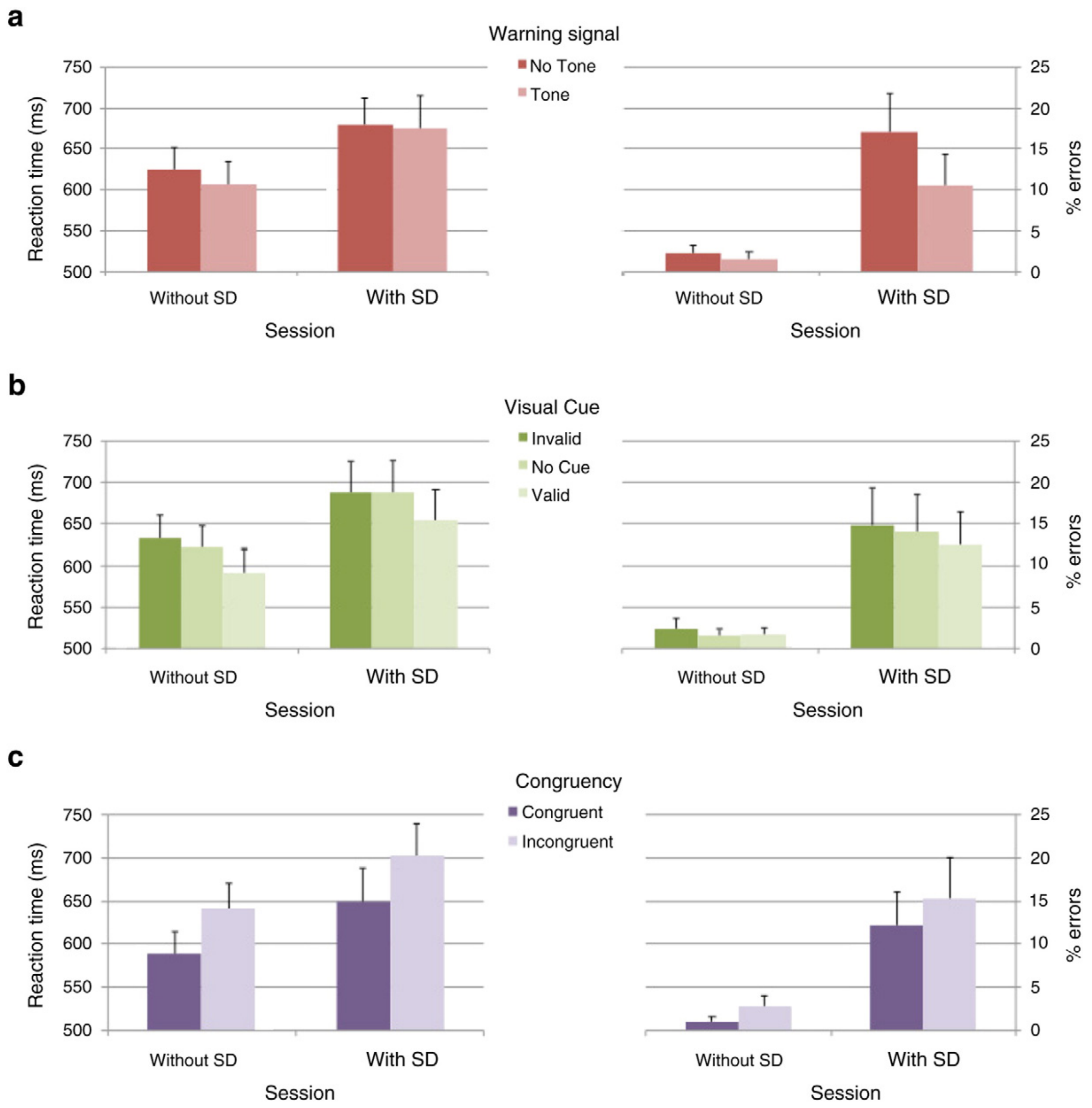

Fig. 2. Interactions involving the sleep deprivation (SD) manipulation. Average results in reaction time (left) and accuracy (right) are shown for: a) Session (Without SD/With SD) × Warning Signal (No tone/Tone) interaction; b) Session (Without SD/With SD) × Visual Cue (Invalid/No cue/Valid) interaction; and c) Session (Without SD/With SD) × Congruency (Congruent/Incongruent) interaction. Error bars represent 95% confidence interval of the mean.

hourly measures ($F(27{,}675)=3.51$; $p<.001$; $\eta^2=.12$) and a planned trend analysis showed both a lineal ($F(1{,}25)=10.09$; $p<.01$; $\eta^2=.29$) and a quadratic component ($F(1{,}25)=7.20$; $p<.05$; $\eta^2=.22$). However, the average morning temperature (9–12) after SD was not significantly different from the morning temperature after a normal sleep night ($F(1{,}25)=.62$; $p=.44$; $\eta^2=.02$).

4. Discussion

In the current work, a total sleep deprivation study was carried out, in which the participants' performance on the Attentional Networks Test for Interactions and Vigilance (ANTI-V) was compared. Although previous research has analysed the effects of sleep loss on different attentional tasks, including the original Fan and collaborators' ANT, this is the first time to our knowledge that the ANTI-V, which involves rather different components of attentional functioning, has been used in a SD study. The results obtained with the ANTI-V revealed that, under SD, tonic alertness was reduced whereas a warning tone was more helpful to increase participants' alertness (specially decreasing the percentage of errors). Also, the reorienting costs of having an invalid spatial cue were reduced. In addition, the present study provides further evidence of the usefulness of the ANTI-V as an attentional task providing a measurement of vigilance along with the indices for phasic alertness, attentional orienting and executive control functioning.

4.1. The Attention Networks Tests for Interactions and Vigilance (ANTI-V)

The results obtained in the initial experimental session show that the ANTI-V has been applied successfully in the current study, and the principal findings by Roca et al. (2011) have been replicated. Main effects of warning signal, visual cue and congruency factors, as well as main expected interactions effectively were obtained.

Additionally, the SDT-based vigilance measures (hits, false alarms, sensitivity and response bias) were obtained and the expected pattern of moderate correlations with other proposed indexes for the ANT or the ANTI tasks (such as global RT and “no tone and no cue” RT) was

Table 5
Summary of main attentional measures in the two sleep deprivation (SD) conditions: Without SD and With SD. Mean and standard deviation (between parenthesis) are shown for: a) Attentional scores in reaction time (phasic alertness, orienting and executive control); b) Attentional scores in percentage of errors; c) Reorienting costs and orienting benefits in reaction time and percentage of errors, d) Vigilance measures (Signal Detection Theory indices); and e) Global results (reaction time, percentage of errors and standard deviation of reaction time).

	Without SD		With SD
a) Attentional scores: RT (ms)			
Phasic alertness	35 (32)	*	17 (42)
Orienting	40 (20)		34 (24)
Executive control	54 (25)		53 (27)
b) Attentional scores: % errors			
Phasic alertness	0.7 (2.3)	*	5.2 (6.6)
Orienting	0.7 (2.3)		2.3 (5.5)
Executive control	1.8 (2.1)		3.3 (5.6)
c) Reorienting costs and orienting benefits			
Costs (RT, ms)	11 (19)	*	0 (24)
Costs (% errors)	0.8 (2.3)		0.8 (3.9)
Benefits (RT, ms)	30 (22)		34 (31)
Benefits (% errors)	−0.1 (1.5)		1.6 (4.7)
d) Vigilance measures (SDT)			
Hits (%)	57 (17)	*	45 (16)
False alarms (%)	1.7 (1.1)		2.4 (1.8)
Sensitivity (d')	2.3 (0.5)	*	1.9 (0.5)
Response bias (β)	9.8 (3.8)		8.4 (4)
e) Global results			
ANTI RT (ms)	615 (66)	*	677 (92)
ANTI % errors	1.9 (2.0)	*	13.7 (10.4)
ANTI St. Dev.	148 (51)	*	217 (71)
Vigilance RT (ms)	775 (78)	*	864 (119)
Vigilance St. Dev.	157 (54)	*	195 (63)

* $p<.05$ (Without SD vs. With SD).

observed. Therefore, as found in Roca et al. (2011), the ANTI-V has been successful in obtaining a direct measure of tonic alertness or vigilance, as well as the usual phasic alertness, attentional orienting and executive control indices.

4.2. The alerting network

Firstly, the comparison of the vigilance indices between the two sleep conditions (with and without SD) provides strong evidence of the validity of the ANTI-V as a vigilance or tonic alertness measure. Sleep loss is considered an effective way to reduce the vigilance level (see, for example, Killgore, 2010; Lim & Dinges, 2008). As expected, the percentage of hits and the sensitivity (d') obtained from the ANTI-V were significantly lower under SD. The percentage of false alarms was slightly higher after a night of sleep loss, although this difference failed to be statistically significant in this study. Consistently with previous evidence, the response bias was similar in both sleep conditions. According to Horne et al. (1983), the β index in a SD study can be considered as a "willingness" to respond positively to the vigilance task and is interpreted as a motivational factor. Thus, we may claim that the motivation to perform the vigilance task was similar in both sleep conditions.

Moreover, these results were accompanied by a slower RT and an increased percentage of errors, which suggests that the change in the vigilance indices was not better explained by a different "attitude towards the task" (i.e., a worse performance in the vigilance task may be expected if the participants do the main task more quickly, for example, if they feel more confident after a repeated presentation of the ANTI-V task). As previously highlighted by Roca et al. (2011), the global measures of RT and accuracy could not be used in isolation to assess the vigilance level, as they are usually influenced by too many factors (for example, they can reflect different strategies for approaching the task), but they can provide convergent evidence to support the direct measure of vigilance obtained from the ANTI-V. Additionally, various results from this study, such as slower overall RT, higher overall percentage of errors, increased RT variability and higher subjective sleepiness (Visual Analogue Scale for "Sleepy"), confirm that the SD procedure was successful in reducing the vigilance level. Also, corporal temperature measures followed the expected circadian rhythmicity.

Secondly, a significant effect on the phasic alertness indices was found after SD, suggesting that the two components (phasic and tonic) of the alerting network may influence each other. In both sleep conditions, a warning signal induced a faster reaction time and fewer errors. However, under SD, the phasic alertness effect was smaller in RT (17 ms vs. 35 ms), whereas the effect in percentage of errors was higher (5.2% vs. 0.72%). Besides, the differences in phasic alertness vanished after introducing the change in sensitivity (d') as a covariate, suggesting that the tonic alertness reduction was the main factor explaining the effect on phasic alertness.

Previous research with the ANT (Martella et al., 2011; Trujillo et al., 2009) failed to find a SD effect on the phasic alertness indices using visual warning signals. However, the ANTI-V uses an auditory signal instead of a visual warning and it has been suggested (Fan et al., 2002) that auditory alerting cues produce more automatic alerting than do visual cues and thus they might serve to aid the reliability of the alerting manipulation (actually, phasic alertness scores were found to be more reliable in the ANTI than in the ANT; Ishigami & Klein, 2010; Lawrence, Eskes, & Klein, 2009). Therefore, the results with auditory alerting cues in the current study indicate that, under reduced vigilance, a warning tone might be more helpful to increase participants' alertness, which results in a slightly faster RT and, particularly, in fewer errors.

These findings on phasic alertness are consistent with the broader sleep loss literature. For example, Cochran et al. (1992) used auditory targets varying in temporal uncertainty and intensity in a sleep deprivation study and found that sleep loss produce its negative effects on RT performance predominantly through the attentional tonic activation system, whereas the phasic alertness system remains relatively preserved (and thus a warning signal can be more helpful under sleep deprivation). Besides, Sanders et al. (1982) found that auditory signals, especially when they are more intense (arousing), further improved RT performance as compared to visual signals. Also, they observed a general increased of missed trials in their experiment, except when these intense auditory signals were presented. More recently, it has been claimed (Posner, 2008) that larger phasic alerting effects generally arise when one group of participants has difficulty in maintaining tonic alertness. Consequently, a greater advantage in performance with a warning tone signal has usually been associated with groups of participants with reduced vigilance (see, for example, Miró et al., 2011). The results with the ANTI-V task may be consistent with this idea, although only with accuracy data.

Additionally, it should be noted that a warning signal generally tends to produce a faster reaction time and a higher error rate (Posner & Petersen, 1990) and this pattern has been also found with the ANT and the ANTI tasks (see, for example, Ishigami & Klein, 2009). According to Posner and Petersen (1990), in states of high alertness, the selection of a response occurs more quickly, based upon a lower quality of information, thus resulting in an increase in errors. In contrast, with the ANTI-V task, the warning tone usually produces a faster RT and a lower error rate (see, also, Roca et al., 2011). It is possible that, as the ANTI-V is a more demanding task than the ANT or the ANTI and overall RT is usually slower, the participants have more time to correctly classify the target stimuli (even when a warning tone has been presented). Thus, an increase in alertness may be able to improve performance, both in RT and accuracy. Also, as shown in the current study, under SD (i.e., a state of low alertness where participants are, again, slower) this particular effect of the warning tone was increased in accuracy.

4.3. The orienting network

The present study failed to find a significant effect of SD on the orienting score (invalid minus valid conditions) using a non-predictive

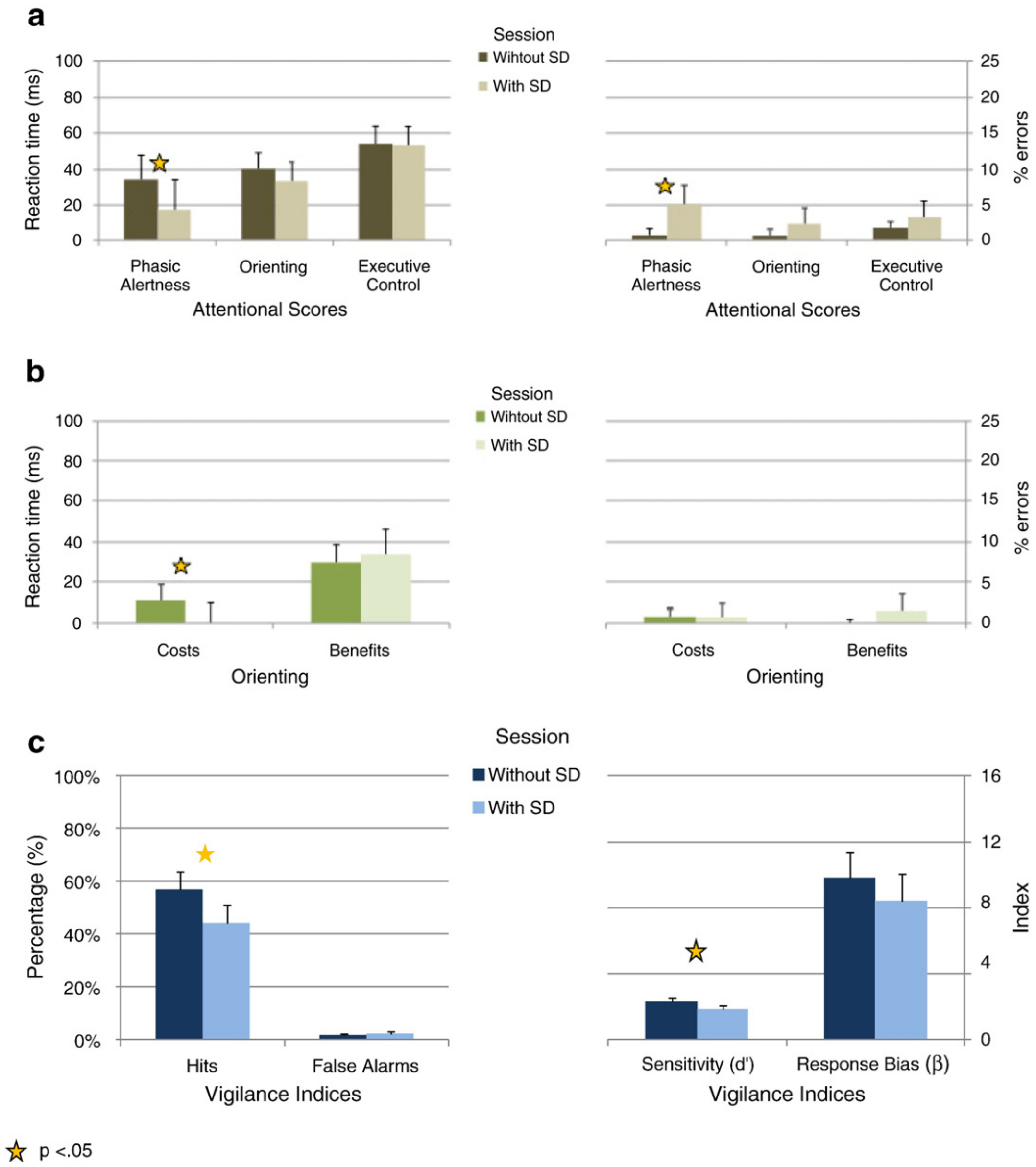

Fig. 3. Main attentional differences between the two sleep deprivation conditions (Session: Without SD/With SD). Average results in reaction time (left) and accuracy (right) are shown for: a) Attentional scores of phasic alertness, orienting and executive control; and b) Reorienting costs and orienting benefits. Also, average vigilance performance indices are shown: c) percentage of hits and false alarms (left) and sensitivity and response bias indices (right). Error bars represent 95% confidence interval of the mean.

peripheral cue. However, a different influence of SD on cost and benefits may result in a clear alteration in the functioning of the attentional orienting network, without observing an effect on the *complete* orienting index (as may happen, for example, if the costs are reduced and the benefits increased after sleep loss). As a consequence, a more detailed analysis of the costs and benefits of attentional cueing was performed and revealed that the reorienting costs of having an invalid spatial cue (invalid minus no cue conditions) were reduced RT under SD, whereas the benefits of presenting a valid spatial cue (valid minus no cue conditions) tended to be slightly higher (although this difference was not statistically significant). Besides, the differences in reorienting costs vanished after introducing the change in sensitivity (d′) as a covariate, suggesting that the tonic alertness reduction was the main factor explaining the effect on this attentional orienting component.

Some relevant dissociations in the orienting costs and benefits have been found previously. For example, Lasaponara, Chica, Lecce, Lupiáñez and Doricchi (2011) manipulated the predictiveness of the orienting cue in a covert attention paradigm and found that by making central cues non-predictive, the costs of reorienting from invalidly cued locations can be selectively reduced while maintaining the benefits provided by valid cuing. Also, these authors pointed out that the costs and benefits are mediated by functionally independent brain mechanisms, as the benefit-related brain activity was reflected by the N1 component and the cost-related activity by the P1 component.

With respect to the SD effects on attentional orienting, Trujillo et al. (2009) used two different cueing tasks (a central and a peripheral predictive task) and found that the N1 component was differently affected by sleep loss and cue manipulation: as compared to regular sleep, the N1 amplitude of validly and neutrally cued targets was similarly reduced under SD with central cueing (thus, similar benefits were observed after normal sleep and after SD). However, with peripheral cues, the N1 response to the validly cued targets was preserved after SD, whereas the amplitude with neutrally cued targets was reduced, leading to greater benefits under SD. No difference in the P1 component was found in this study, although it should be noted that no invalid cues were used and therefore it was not possible to analyse the reorienting costs. Also, Martella et al. (2011) used a peripheral predictive cueing task and found higher benefits in RT under SD, suggesting that peripheral spatial

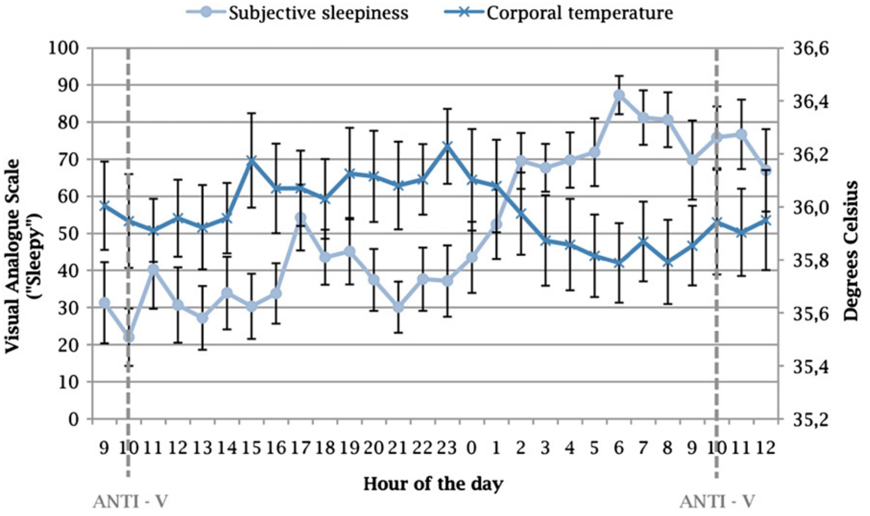

Fig. 4. Subjective sleepiness (Visual Analogue Scale for "Sleepy") and corporal temperature (degrees Celsius) average measures in the sleep deprivation study. A total of 28 measures were taken hourly from 9.00 a.m. after a normal sleep night (Without SD) until the end of the sleep deprivation study (With SD). The vertical dotted lines indicate the moments where the attentional task (ANTI-V) was performed.

cues were more helpful after sleep loss. Again, no invalid cues were used in this study and thus the influence of SD on reorienting costs was not analysed. However, Versace et al. (2006) used a peripheral predictive task with valid, invalid and neutral cues in a partial SD study. These authors found that RT was higher after SD with invalid cues, which was somehow expected as lack of sleep usually increases RT. More interesting was the null effect of SD observed with valid cues (no increase in RT was observed after SD in this case), which is consistent with the idea of valid peripheral cues being more useful after sleep loss. Finally, Casagrande et al. (2006) failed to find differences after SD with a central predictive task with valid, invalid and neutral cues. RT was similarly increased by sleep loss in each cue condition and thus the endogenous components of attentional orienting may be similarly affected by sleep loss.

Overall, it is proposed that the alerting and the orienting networks can influence each other, in the sense that a reduced tonic alertness after SD may be more detrimental to the endogenous (voluntary) components of attentional orienting while the exogenous (automatic) components will be more resistant. As a consequence, different results will be expected in SD studies using central vs. peripheral cueing tasks and also by analysing the reorienting costs and the orienting benefits separately. Central cueing tasks involve mainly endogenous attention, and thus the different orienting components may be similarly affected by SD and an overall increase in RT will be found. Also, the reorienting costs are endogenously influenced (as shown by Lasaponara, Chica, Lecce, Lupiáñez, & Doricchi, 2011) and thus will be reduced after SD. On the other hand, peripheral cueing is more automatic and thus peripheral valid cues will be more helpful after sleep loss, compensating for the general increase in RT.

Finally, previous evidence has also found an interaction between the alerting and orienting networks using a phasic alertness manipulation. For example, Callejas et al. (2004) and Fuentes and Campoy (2008) found that a warning tone enhanced the orienting score. The same result has also been found in the SD study, where the cueing effect was greater for the tone than the no tone conditions. As a consequence, it is suggested that increasing the alertness level (for example, by presenting a warning cue) interacts with the functioning of the orienting network, making the orienting effect greater.

4.4. The executive control network

No SD effect was found in the present study on the executive control score. The literature on the influence of SD on this network has shown inconsistent results (see, for example, Killgore, 2010). In the current study, results may suggest that SD has no influence on the congruency effect measured by the ANTI-V. This is inconsistent with previous studies using the ANT (Martella et al., 2011), where a higher congruency effect (more interference) was found after sleep loss. However, in Martella et al.'s study the attentional task was performed at 4 a.m. and compared to previous 5 p.m. Thus, the effect found on executive control can also be explained by a circadian factor as well as to homeostatic sleep pressure. Yet, it should be noted that the ANTI-V task requires a further vigilance component compared to the ANT task, and the need for cognitive control is increased to adequately distinguish the different types of stimuli (Roca et al., 2011). Therefore, the increased cognitive control mechanism may have partially compensated the effect of SD on the executive control score and no larger interference was observed. This suggestion is consistent with previous evidence showing that sleep deprived participants may perform better as tasks become more complex. For example, Baulk et al. (2001) found that adding a secondary reaction time task provided more activity and stimulation for sleepy drivers during a monotonous drive and as a consequence their performance was improved. Besides, Drummond et al. (2004) found that task difficulty facilitates cerebral compensatory responses after sleep deprivation, which manifested as an increased neural activity in the absence of significant performance differences with behavioral data. Also, the inconsistent results on executive control could be ascribed to the reported high inter-subject variability of the effects of sleep loss (Banks & Dinges, 2007; Bell-Mcginty et al., 2004; Van Dongen et al., 2004).

Finally, the warning signal and congruency interaction was statistically significant in the SD study, as opposed to previous results with the ANTI-V task. The congruency effect was higher when a warning tone had been presented than when the tone was absent. This warning signal × congruency interaction is consistent with the data obtained with the ANTI (Callejas et al., 2004), but it was unexpected using the ANTI-V, as both the results by Roca et al. (2011) and the data in the initial experimental session of the current study suggested an absence of interaction. However, separate analyses for the without SD and the SD session failed to confirm this interaction, suggesting that the interaction effect may be unreliable and, possibly, was only present in the SD session (where an unconfirmed tendency was observed).

It should be noted that the without SD and SD sessions were the second and third time that the participants completed the ANTI-V task (the first time was the initial experimental session performed on the afternoon previous to the SD day, aimed at reducing the impact of possible learning effects that may appear after a repeated presentation of the ANTI task; see Ishigami & Klein, 2010). Therefore, future research would be useful to explore the potential effect of a repeated presentation of the ANTI-V on the warning signal × congruency interaction.

Also, it is possible that the SD manipulation affected the way in which the phasic alertness modulates the executive control network in the ANTI-V. Generally, the ANTI-V is considered to be a more demanding task (compared to the ANT of the ANTI) and, as argued above, the need for cognitive control is increased to adequately distinguish the infrequent displaced target from the frequent centred target (Roca et al., 2011). Thus, the warning signal and congruency interaction is absent because the congruency effect is quite low, even in the presence of a warning signal. However, under SD, it is more difficult to maintain cognitive control and thus the interaction between a warning signal and the congruency effect can again be observed. Nevertheless, this suggestion should be considered carefully, as we failed to find a significant SD effect on the congruency index in the present study.

5. Conclusions

The present study provides new evidence to evaluate the influence of sleep deprivation on attentional functioning. Firstly, as expected, tonic alertness was reduced by sleep loss. A poorer performance in vigilance tasks is usually found under SD (Killgore, 2010), and thus these results show that the ANTI-V is useful to obtain an appropriate vigilance measure. Interestingly, differences in phasic alertness functioning were found after SD, whereas previous evidence failed to find significant results using the ANT with visual warning signals (Martella et al., 2011; Trujillo et al., 2009). Since it has been shown that the use of auditory warning signals, as in the ANTI-V, is associated with an increased reliability of the measurement (Fan et al., 2002; Ishigami & Klein, 2010; Lawrence et al., 2009), it is proposed that under SD, a warning tone might be more helpful to increase participants' alertness, which results in a slightly faster RT and, especially, in fewer errors.

Secondly, the attentional orienting function was also affected by sleep loss, showing that the reorienting costs of having an invalid spatial cue were reduced. Based on these results and the evidence from previous studies (see discussion in Section 4), it is suggested that SD may be more detrimental to the endogenous (voluntary) components of attentional orienting while the exogenous (automatic) components will be more resistant.

Thirdly, in relation to the executive control network, no SD effect was found in the present study. It has been claimed that the need for cognitive control is increased in the ANTI-V to adequately distinguish the different types of stimuli (Roca et al., 2011) and this may have partially compensated for the effect of SD on the interference measure. Also, the inconsistent results that were found with regard to executive control functioning (Killgore, 2010; Martella et al., 2011) could be ascribed to the reported high inter-subject variability of the effects of sleep loss (Banks & Dinges, 2007; Bell-Mcginty et al., 2004; Van Dongen et al., 2004).

The main limitation of the present study is that no control group was included in the experimental design and therefore results on SD may be partially influenced by the repeated presentation of the attentional task. In fact, some learning effects have been previously reported for the ANTI (Ishigami & Klein, 2010). As participants complete repeatedly the attentional task, both the orienting score and the executive control tend to decrease (due to better performance on, respectively, invalid cues and incongruent flankers) and no significant effect was found on the alerting score. However, it should be noted that these learning effects were particularly intense between the first and the second presentation of the task (as shown in Fig. 2 in Ishigami and Klein's study). Therefore, as it has been done in the current study, introducing an initial experimental session (first presentation of the task) and then comparing the second (Without SD) and the third (With SD) presentations of the attentional task may have minimised the impact of the potential learning effects. Besides, additional analyses were performed to provide further evidence supporting that the differences reported in the attentional functioning were effectively due to a tonic alertness reduction. In particular, the change in sensitivity (d′) between the two sessions (With SD minus Without SD) was introduced as a covariate and the differences in the attentional scores were compared in separate ANCOVAs. After introducing the covariate, the differences in the attentional scores vanished, suggesting that the tonic alertness reduction was the main explanatory factor. Yet, further research with the ANTI-V and alternative tasks, using both behavioural and neurophysiological data, will be useful to clarify the influence of SD on the different components of attentional system.

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