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RESEARCH ARTICLE

Alerting, orienting and executive control: the effects of sleep deprivation on attentional networks

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Abstract Sleep deprivation alters attentional functions like vigilance or tonic alerting (i.e., sustaining an alert state over a period of time). However, the effects of sleep loss on both orienting and executive control are still not clear, and no study has assessed whether sleep deprivation might affect the relationships among these three attentional systems. In order to investigate the efficiency of the three attentional networks—alerting, orienting and executive control—within a single task, we used the Attention Network Test (ANT). Eighteen right-handed male participants took part in the experiment, which took place on two consecutive days. On the first day, each participant performed a 20 min training session of the ANT. On the second day, participants remained awake for 24 h during which time the ANT was performed once at 5:00 p.m. and once at 4:00 a.m. Results showed an overall slowing of reaction times in the nocturnal session, indicating a strong decrease in vigilance. Furthermore, sleep deprivation did affect attentional orienting and executive control. Results are consistent with the hypothesis that the tonic component of alerting interacts with both attentional orienting and executive functions.

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Introduction

The behavioural and cognitive effects of sleep deprivation (SD) are well known (Hill 2004). Sleep loss increases sleepiness (Carskadon and Dement 1979; Gillberg et al. 1994) and negatively affects performance on cognitive tasks (e.g., Heuer et al. 2005; Sagaspe et al. 2006). These aspects are very relevant for understanding the consequences of sleep loss as the cognitive demands of work increase, and night work becomes more frequent. To this end, evaluating performance when participants are submitted to a moderate sleep loss can be very useful. Indeed, exploring the effects of this kind of SD seems to represent a good match with what happens in real life, when people are requested to sustain wakefulness for 24 h (i.e., a physician in an intensive care unit, a fireman in disaster evacuation, military pilots during intense operations) (e.g., Barger et al. 2006; Tsai et al. 2005). In fact, sleepiness due to factors such as reduced sleep or extended time awake has been associated with occupational and transportation accidents, industrial catastrophes and medical errors (e.g., Barger et al. 2006; Connor et al. 2001; Mittler et al. 1988; Philip 2005; Philip and Akerstedt 2006).

The present study aimed to investigate how the functioning of the attentional networks (alerting, orienting and executive control; Fan et al. 2005) change with moderate SD (i.e., the first hours of the night without sleep) and circadian factors (i.e., night-time hours). When SD is manipulated this way, two potential sources of influence may affect the decrease in vigilance: one is sleep loss *per se* and the other is the circadian variation (e.g., Dijk and Czeisler 1995; Lavie 2001). However, at present, we are primarily concerned with a manipulation of vigilance. This type of SD, namely extended wakefulness beyond the usual evening time sleep onset, is particularly useful because it decreases vigilance (Casagrande et al. 2006) in an ecologically valid manner, allowing us to better understand alerting, orienting and executive attentional functions when people are drowsy. Consequently, this experimental paradigm can be useful in assessing interactions among these three attentional systems.

Among the functions that have been reported to suffer from one night of total SD, one of the most prominent seems to be attention. In fact, it is usually recognized that performance decrements after sleep loss are mainly due to attentional deficits (Dinges 1992; Kjellberg 1977)—an explanation that considers attention as a unitary construct. However, cognitive researchers agree upon the idea that attention is a multidimensional ability (Posner and Petersen 1990; Fan et al. 2003; Raz 2004), which can be considered concretely as an organic system (Posner and Fan 2008). This system involves three specialized neural networks and neuromodulators subserving different attentional functions: (1) Alerting—defined as achieving (phasic alerting) and maintaining (tonic alerting or vigilance) a general state of activation of the cognitive system. (2) Orienting—that selectively allocates the attentional focus to a potentially relevant area or object of the visual field; (3) Executive Control—defined as the ability to control our own behaviour in order to achieve intended goals, resolving conflict among alternative responses (e.g., Fan et al. 2009).

It is well known that SD affects the alerting system, as reflected by reaction time tasks (Dinges et al. 1997; Mikulincer et al. 1989; Urrila et al. 2007; Van den Berg and Neely 2006). In fact, a negative correlation between brain activation in the alertness network and RT has been well-documented (e.g., Fan et al. 2005). The opposite findings have also been reported (e.g., Yarkoni et al. 2009) although with different tasks. However, due to many inconsistent results, the effects of reduced vigilance due to sleep loss and circadian factors on orienting and executive control are still not clear. Regarding orienting, few studies have addressed this issue using a Covert Attention Task (Posner 1980). In this task, spatial orienting can be manipulated by presenting a spatial cue, which comes before target presentation, and can be either valid or invalid with regard to target location. Studies evaluating the relationship between a decrease in vigilance and orienting have led to contrasting results (Bocca and Denise 2006, Casagrande et al. 2006; Fimm et al. 2006; Versace et al. 2006).

Specifically, Casagrande et al. (2006) found a general decrease in arousal (a significant increase in RT) across 24 h of sustained wakefulness, but not a selective effect on the orienting mechanisms. On the other hand, Versace et al. (2006), using a partial sleep reduction paradigm, observed a significant slowing down of RT in the invalid condition, indicating an impairment of the reorienting mechanism. A similar interaction between alerting and orienting was confirmed by other authors (Bocca and Denise 2006; Fimm et al. 2006). One of the most relevant differences among these studies concerns the type of manipulation used to measure the orienting process. An interaction between the two systems was observed in the investigations (Bocca and Denise 2006; Fimm et al. 2006; Versace et al. 2006) that used a peripheral predictive cue, but it was not found by Casagrande et al. (2006), who used a central predictive cue. The main difference between these two types of tasks can be ascribed to some characteristics of the attentional processes involved. In fact, it is known that a central symbolic cue affects a voluntary shifting of attention (Posner 1980); while a peripheral predictive cue allows an attentional orienting characterized by both automatic and voluntary processes (Jonides 1981; Ivanoff and Klein 2003). On the basis of these differences, one may conclude that orienting and alerting networks seem to interact when people have to perform a task involving bottom-up components of attention. This conclusion is in line with the finding of a greater orienting effect under increased phasic alertness—i.e., an interaction between alerting and orienting—when peripheral non-predictive cues are used (Callejas et al. 2004, 2005; Fuentes and Campoy 2008).

As regards the executive control system, this can be investigated by means of different tasks such as the colour or spatial Stroop tasks, Flanker tasks, Simon tasks, Go-NoGo tasks, word fluency tasks and many others. This wide range of evaluation tasks depends on the broad behavioural control exerted by the executive system, including behavioural planning, decision-making, error discovery, finding and resolving a cognitive conflict, and the ability to inhibit actions (e.g., Fan et al. 2002, 2009; Heil et al. 2000; Posner and DiGirolamo 2000). Many studies have found that SD impaired executive functions (e.g., Gosselin et al. 2005; Harrison and Horne 1997, 1998, 2000; Harrison et al. 2000; Heuer et al. 2004; Jones and Harrison 2001; Killgore et al. 2006; Lingenfelser et al. 1994; McCarthy and Waters 1997; McKenna et al. 2007; Nilsson et al. 2005; Tsai et al. 2005), whereas others did not (Binks et al. 1999; Fallone et al. 2001; Sagaspe et al. 2003). Thus, Binks et al. (1999) showed that short-term SD has no effect on a Stroop task, a Wisconsin Card Sorting Test and a word fluency task. Similarly, Fallone et al. (2001) did not observe any impairment in performance in inhibition tasks following sleep reduction, and Sagaspe et al. (2003) found no effect of 36 h of sleep loss in a short task requiring random letter generation.

Given these contrasting data, it seems necessary to evaluate the effects of moderate SD on attentional networks by using a single task manipulating alerting, orienting and executive control at the same time. To this end, we used the Attention Network Test (ANT) developed by Fan et al. (2002) and asked participants to perform the ANT at 5 p.m. and 4.00 a.m. (two time windows corresponding, respectively, to a "forbidden zone" for sleep and to the main "sleep gate"; see Lavie 2001), in order to evaluate the effects of reduced vigilance by SD on attentional functioning. The ANT is a combination of a covert attention task (Posner 1980) and a flanker task (Eriksen and Eriksen 1974). Participants have to indicate the direction a central arrow is pointing to. This central arrow is flanked by two arrows on both sides and which may be pointing in the same direction (congruent condition) or opposite one (incongruent condition). The difference between these two conditions is considered as an index of executive control functioning. The conflict effect is calculated by subtracting the mean RT of congruent flanking conditions from the mean RT of incongruent flanking conditions. The two conditions differ only in the information given by flankers that provide a facilitating effect on target stimulus discrimination when they are congruent, while they distract participants when they are incongruent. Therefore, the RT difference between congruent and incongruent flankers allows to measure executive control on conflicting information.

Furthermore, visual cues are used in order to separately assess the alerting (improved performance following a non-spatial warning cue) and orienting (an additional benefit when the cue correctly indicates the target location) attentional functions. When both no-cue and double-cue are presented, attention tends to remain diffused across the two potential target locations and neither of these conditions provided spatial information about the target stimulus position, but double-cue alerts the participant to the imminent appearance of the target. Therefore, the alerting effect is calculated by subtracting the mean RT of the double-cue conditions from the mean RT of the no-cue conditions. This effect represents the benefit of the target response speed because of alerting.

The validity effect was calculated by subtracting the mean RT of the spatial cue conditions from the mean RT of the centre cue. Both centre and spatial cues alert participant about the imminent appearance of the target, but only the spatial cue provides spatial information that allows subjects to orient attention to the appropriate spatial location. Therefore, the RT difference between spatial and centre cue provides a measure of orienting attention (Fan et al. 2002, 2009).

The ANT was used for several reasons: (1) It is short (20 min) and simple. This factor is remarkable considering the inconsistent results regarding the impact of SD on executive functions (e.g., Harrison et al. 2000; Sagaspe et al. 2003). In addition, using the ANT might be useful because it provides an independent measure of each attentional network, allowing us to evaluate how the three are modulated by tonic alertness. (2) Using the ANT will allow assessment of the relationships among the attentional systems (independence/interaction).

Previous studies using the ANT claimed independence of the three attentional networks in adult participants (Fan et al. 2002) and 7-year-old children (Rueda et al. 2004). However, the fact that the three attentional networks can work independently does not mean they do not interact when working to coordinate behaviour in order to reach a specific goal. In fact, interactions between the three attentional networks have been reported in other studies (Callejas et al. 2004, 2005; Fuentes and Campoy 2008). Accordingly, a SD paradigm would allow us to assess not only its effects on each attentional system but also to appraise the relationship between alerting and the two other attentional networks (orienting and executive control), when the former is manipulated in an independent way. In this case, at variance with other studies (Callejas et al. 2004, 2005; Fuentes and Campoy 2008), we did not manipulate phasic alerting but tonic alertness, which was reduced by both sleep loss and circadian factors (Lavie 2001).

Based on these considerations and previous studies (e.g., Casagrande et al. 2006), we expected a decrease in tonic alertness at 4.00 a.m. when compared to 5.00 pm. We expected this impairment of alertness to be expressed as an increase in RT that would also be corroborated by the corresponding increase in subjective sleepiness. If tonic changes in alertness do affect orienting in the same way as a phasic change does, then an interaction between alerting and orienting should be observed. Specifically, since a phasic increase in alertness has been shown to cause a faster (e.g., Callejas et al. 2004) or more pronounced (Fuentes and Campoy 2008) orienting, a reduced orienting effect should be observed under a decrease in alertness (i.e., under SD). As regards executive functions, inconsistent results have been reported under reduced vigilance (e.g., Hsieh et al. 2007; Murphy et al. 2006; Tsai et al. 2005), even though studies underlining a worsening of executive control under SD are more numerous than those observing no effect. On the basis of these results, either an impairment of executive functions or no effect is plausible, but the former prediction is more likely.

Methods

Participants

Eighteen male university students (mean age: 23 ± 2.6) signed an informed consent before participating as volunteers in the study. The study was approved by the local ethical committee. The participants were selected as being right-handed having a Hand Preference Index > .85, as assessed by means of a Lateral Preference Questionnaire (Salmaso and Longoni 1985). They were all naïve to the purpose of the experiment and all of them reported normal or corrected to normal vision. At home, participants were asked to daily complete a sleep questionnaire upon final awakening in the morning, for 1 week before the experimental session. Only participants who reported a 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, participants did not drink or eat anything containing caffeine (e.g., coffee, tea, chocolate).

Apparatus

The stimuli were programmed and presented via E-Prime software (Psych. Software Tools 1996) on a Pentium 4 computer, presenting on a 21-inch colour VGA monitor. The responses were collected through the computer keyboard.

Stimuli and procedure

For an extensive and detailed description of both stimuli and procedure, see Fan et al.'s (2002) study. The stimuli consisted of a row of five horizontal black lines, presented on a grey background (see Fig. 1). The target was a left- or right-point arrow at the centre, which was flanked on both sides by two arrows pointing either in the same direction (congruent trials), or in the opposite direction (incongruent trials), or by lines (neutral trials), see Fig. 1c. A single arrow or line consisted of .58° (degrees of visual angle) and the contours of adjacent arrows or lines were separated by .06°. The stimuli (one central arrow plus four flankers) subtended a total of 3.27°. The target and flankers were presented 1.06° above or below the fixation point.

The display was in a silent and dimly illuminated room at a distance of 56 cm from the participant's eyes. A headrest was used to stabilize the observer's head. Each trial consisted of these events: a fixation period of variable duration (400–1,600 ms), a cue presented for 100 ms and the target display, which was presented 400 ms after the cue. The target and flankers were presented until the participant responded or up to 1,700 ms (Fig. 1a). Each trial lasted 4,000 ms. The fixation point appeared in the centre of the screen during the whole trial. Congruency between target and flankers was used to measure the executive control network, and four cue conditions were used to measure efficiency of both the alerting and orienting networks: the no-cue (baseline) and double-cue (one cue at each of the two possible target positions) condition allowed estimating alerting; the centre-cue (cue at fixation) and spatial-cue (a cue 100% predictive of the target location, and appearing previously at its same location) conditions allowed evaluating orienting (Fig. 1b). After a 24-trial practice block, participants performed three experimental blocks. Each one consisted of 96 trials (4 cue conditions × 2 target locations × 2 target directions × 3 flanker conditions × 2 repetitions). Each experimental block lasted about 6.4 min and the ANT—including breaks—lasted about 24 min.

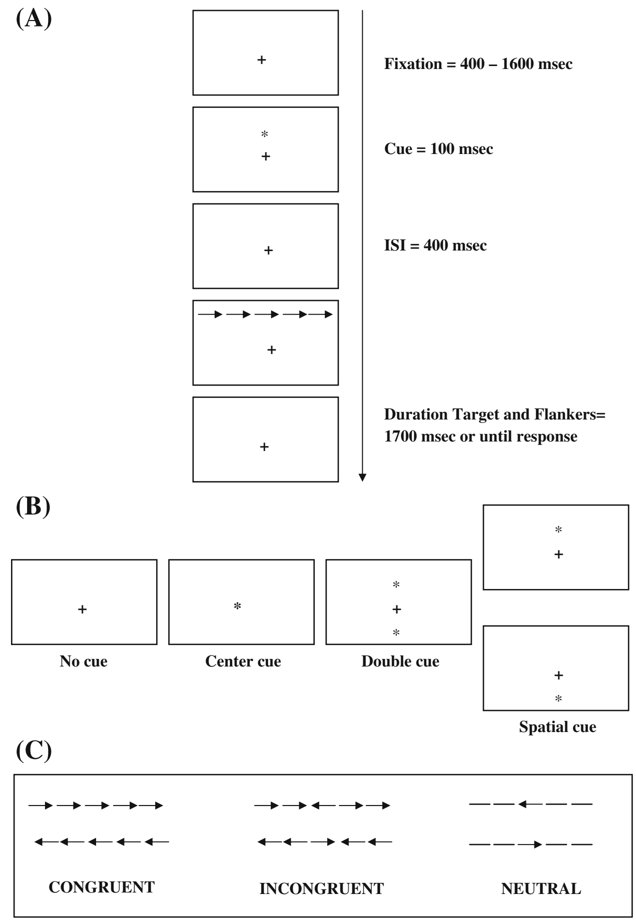


Fig. 1 The figure reports: **a** an example of the procedure; **b** the cue conditions, from left to right are, respectively, reported no-cue, centre-cue, double-cue and spatial-cue conditions; **c** the flanker stimuli used in the ANT. Size and proportions of the stimuli do not match those actually used and are given only as an example

The sequence of events for each trial is shown in Fig. 1.

Task

The participants' task was to identify the direction of the centrally presented arrow by pressing one key for the left direction and a different key for the right direction.

Subjective measures

We used a unidimensional Visual Analogue Scale (VAS) (Curcio et al. 2001), which required each participant to assess "how do you feel right now" with respect to the adjective "sleepy". Participants responded by making a stroke with a pen on a 100 mm long line. The stroke had to correspond to the point indicating the intensity of the self-evaluation. The VAS anchored at one end with "not at all" (on the left) and at the other end with "very much" (on the right). The distance of the mark from the left end of the line was considered as a dependent variable.

General procedure

The experiments were run on two consecutive days. In the morning of the first day, participants came individually to the laboratory and were given detailed information about the procedure; they then performed the training task, i.e. a 20 min session of the ANT. On the second day, after participants slept their usual 8 h, they were kept awake for 24 h and were required to perform the ANT at 5.00 p.m. (Baseline: BSL) and at 4.00 a.m. (SD). The ANT was performed individually, in a sound attenuated air-conditioned room. Before and after the ANT, participants performed other cognitive tasks; the VAS was compiled hourly by the participants. The participants had two breaks, one for lunch (about 1.00 pm) and one for dinner (about 8.00 pm), during the 24-h period. The experimenter continuously monitored the participants in order to avoid any naps.

Experiment design

All data are presented as mean ± SD. For data analysis, only reaction times (RT) ranging between Mean RT−2SD and Mean RT + 2SD ms were used. As the RT to neutral and congruent flankers did not differ ($P = .73$), RT on neutral trials were disregarded from subsequent analyses. A *Session* (BSL, SD) × *Cue* (Spatial, Central, Double, No-cue) × *Flanker* (Congruent, Incongruent) repeated measures ANOVA was performed on both mean corrected RT and the number of misses, defined as RT slower than Mean RT + 2SD (e.g., Chee et al. 2008). These three factors were, respectively, considered in order to evaluate variations in the alertness, orienting and executive functions. Furthermore, in order to estimate the efficiency of each attentional system and to compare the results of this study with previous studies using the ANT (Callejas et al. 2004, 2005; Fan et al. 2002; Fuentes and Campoy 2008), separate one-way ANOVAs considering only the *Session* factor (BSL, SD) were performed on the following dependent variables: the *validity effect* (RT centre-cue–RT spatial-cue), in order to assess the orienting system; the *alerting effect* (RT no-cue–RT double-cue), to evaluate the alertness system; and the *conflict effect* (RT incongruent trials–RT congruent trials), indexing the executive control system. Finally, subjective sleepiness was analysed by means of one-way ANOVA considering the factor *Session* (1–24). In order to remove proportionality between means and variance of subjective measures, raw data were submitted to natural logarithmic [ln (x + 1)] transformation and, in order to correct for the non-sphericity of the data, the Greenhouse-Geisser correction of the degrees of freedom was employed if required. Trend analyses were used in order to analyse the trend over the 24 h of subjective measures of sleepiness whereas LSD test was performed in order to analyse both cue and flanker effects.

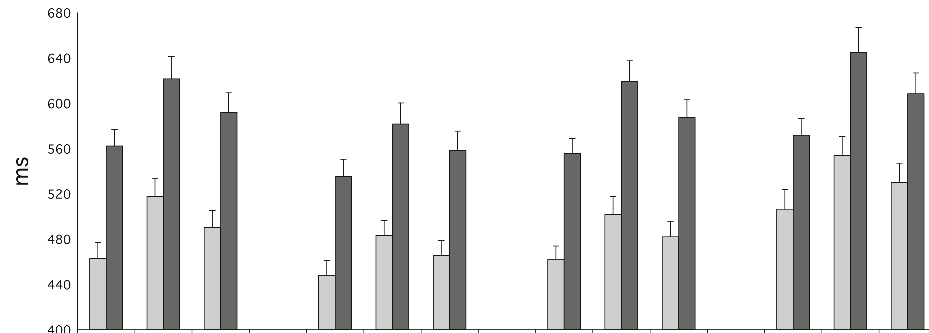
Table 1 Mean (± SD) corrected RT for each condition in both baseline and sleep deprivation sessions

Cue	Session			
	Baseline		Sleep deprivation	
	Congruent	Incongruent	Congruent	Incongruent
Central	462.96 (59.62)	562.41 (61.53)	517.86 (67.45)	621.66 (83.98)
Double	462.20 (49.69)	555.63 (56.48)	501.92 (67.83)	619.11 (77.98)
Spatial	448.17 (54.81)	535.27 (64.86)	483.30 (55.96)	581.69 (79.17)
No-cue	506.47 (73.89)	571.88 (62.84)	553.95 (70.47)	644.88 (93.41)

Results

Trials with RT faster than the Mean RT−2SD were .23% of the trials and RT slower than the Mean RT + 2SD (misses) were 5% of the trials and were all removed from the analyses. Trials with erroneous responses accounted for 2.30% of the trials. Table 1 shows the mean (±SD) RT for each experimental condition for both BSL and SD sessions.

The ANOVA performed on mean correct RT showed a significant effect for *Session* ($F_{1,17} = 27.26$; $P < .0001$), with slower RT in the SD session (Mean RT: 565.54 ms) than in BSL (Mean RT: 513.12 ms). The main effect of *Cue* ($F_{3,51} = 31.98$; $P < .0001$) was also significant and revealed that when the target was presented in the same position as the cue (Mean RT: 512.10 ms), participants were faster than in the centre-cue (Mean RT: 541.22 ms; $P < .0001$), no-cue (Mean RT: 569.29 ms; $P < .0001$) and double-cue (Mean RT: 534.71 ms; $P < .001$) conditions. Also, participants were slower in the no-cue condition than in the double-cue ($P < .001$). The main effect of *Flanker* ($F_{1,17} = 186.53$; $P < .0001$) was significant, showing faster RT for congruent (Mean RT: 492.10 ms) than incongruent flankers (Mean RT: 586.56 ms). The *Session* × *Flanker* interaction ($F_{1,17} = 6.41$; $P < .05$; Fig. 2) revealed a greater

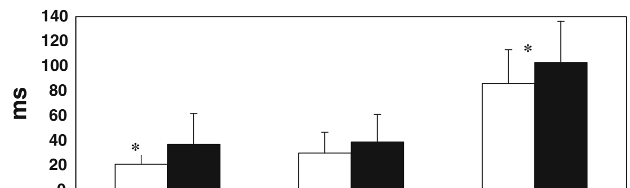


	BSL	SD	M		BSL	SD	M		BSL	SD	M		BSL	SD	M
Congruent	463	518	490		448	483	466		462	502	482		506	554	530
Incongruent	562	622	592		535	582	558		556	619	587		572	645	608
	CENTRAL				SPATIAL				DOUBLE				NO-CUE		

Fig. 2 Mean reaction times (*RT*) and SE for congruent and incongruent flankers as a function of the cue type (from left to right: centre, spatial, double and no-cue conditions). For each cue-type, from left to right, baseline (*BSL*), sleep deprivation (*SD*) and mean (*M*) RT between BSL and SD conditions are reported

congruency effect in the SD (congruent: 514.26 ms and incongruent: 616.83; congruency effect = 103 ms) than in the BS condition (congruent: 469.95 ms and incongruent: 556.30 ms; congruency effect = 86 ms).

The *Session* × *Cue* interaction was significant ($F_{3,51} = 3.40$; $P < .05$; Fig. 2), showing different alerting or orienting effects in the SD than in BSL session, as was the *Cue* × *Flanker* interaction ($F_{3,51} = 4.68$; $P < .01$; Fig. 2). In order to determine whether these differences were due to alertness or to attentional orienting, the *Cue* × *Flanker* interaction was explored by using two different ANOVAs. A 2(Session) × 2(*Flanker*) × 2(Cue) ANOVA was performed on the centre versus spatial-cue in order to investigate the Orienting × Conflict interaction. The same ANOVA was carried out on the no-cue versus double-cue in order to investigate the Alerting × Conflict interaction. The ANOVA exploring the Orienting × Conflict interaction confirmed significant effects for Session ($F_{1,17} = 19.53$; $P < .001$), Cue ($F_{1,17} = 17.58$; $P < .001$) and Flanker ($F_{1,17} = 226.04$; $P < .0001$). The Session × Cue interaction ($F_{1,17} = 10.85$; $P < .005$) showed that the validity effect was greater in SD condition (37 ms) than in BSL (21 ms). This effect was due to a greater increase of RT in the Centre-cue trials (57 ms) than in those with spatial cue (41 ms). All the other interactions were not significant ($F < 1.5$). The ANOVA investigating the Alerting × Conflict interaction confirmed significant effects for Session ($F_{1,17} = 36.20$; $P < .0001$), Cue ($F_{1,17} = 31.08$; $P < .0001$) and Flanker ($F_{1,17} = 128.52$; $P < .0001$). The Session × Flanker interaction ($F_{1,17} = 6.68$; $P < .05$) showed that although RT were slower in the incongruent condition in both sessions ($P < .0001$), the conflict effect was greater in the SD condition (104 ms) than in BSL (79 ms). The Cue × Flanker interaction ($F_{1,17} = 14.09$; $P < .01$) showed that RT were faster in the double-cue than in no-cue at all the levels of



	Orienting	Alerting	Conflict
BSL	21	30	86
SD	37	39	103

Fig. 3 Orienting (RT centre-cue–RT spatial-cue), alerting (RT no-cue–RT double-cue) and conflict effects (RT incongruent flankers–RT congruent flankers), in the baseline (*BSL*) and sleep deprivation (*SD*) sessions

the flanker ($P < .001$). Nevertheless, the conflict effect was larger in the double-cue (105 ms) than in the no-cue condition (78 ms). All the other interactions were not significant ($F < 1$).

The ANOVA on the *validity effect* ($F_{1,17} = 10.85$; $P < .005$) showed a larger effect in SD (37 ms) than in BSL condition (21 ms); equally, the *conflict effect* ($F_{1,17} = 6.41$; $P < .05$) was bigger in SD (103 ms) than in BSL condition (86 ms). No variation between the two sessions ($F_{1,17} = .88$; $P = .36$) was found for the *alerting effect* (Fig. 3).

Misses

The number of misses were significantly ($F_{1,17} = 5$; $P < .05$) more frequent in the SD (5%), than in BSL condition (4%).

Subjective measures

The ANOVAs performed on the subjective measure of sleepiness was significant ($F_{6.8,\,116.4} = 10.57$; $P < .0001$

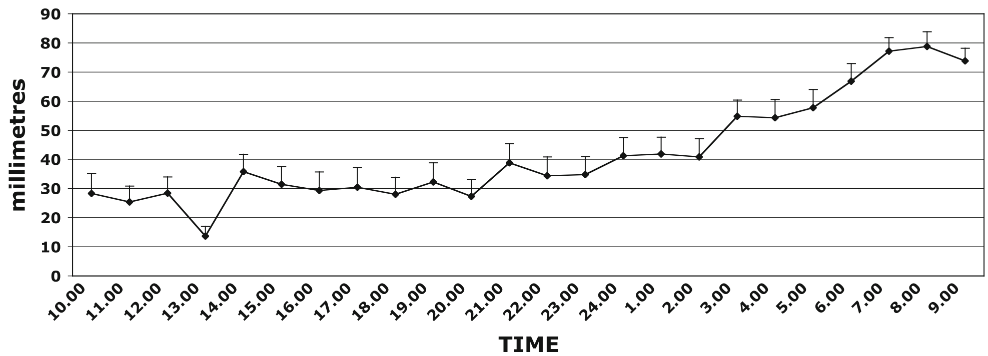


Fig. 4 Mean and SE measures of subjective measure (in mm) of sleepiness through the 24 h of sustained wakefulness

with Greenhouse-Geisser correction; epsilon = .2977; Fig. 4) and trend analyses revealed as significant the linear and quadratic trends ($F_{1,17} = 37.77$; $P < .0001$ and $F_{1,17} = 32.33$; $P < .0001$, respectively), indicating that subjective sleepiness increased with time although the increase really started after 20.00–21.00.

Discussion

Results confirm that the experimental paradigm adopted in this study was able to produce an effective increase in RT during the nocturnal session (4.00 am), replicating other studies adopting the same experimental paradigm, i.e. 24 h of prolonged wakefulness (e.g., Casagrande et al. 2006; Fimm et al. 2006). The efficacy of the experimental manipulation on alertness was corroborated by subjective measures of sleepiness. The effectiveness of the task was also confirmed, as shown by both cue and conflict effects.

Importantly, an effect of vigilance decrease on the orienting mechanisms was observed, contrary to Casagrande et al.'s (2006) study. One may suggest that orienting and alerting can interact when orienting is triggered by exogenous cue, involving bottom-up mechanisms of attention, such as observed in our results, and previous studies (Fimm et al. 2006; Versace et al. 2006). However, since the ANT did not include an invalid cue condition, the ANT did not provide any measure of attentional orienting costs, which seemed to be impaired in other studies (Fimm et al. 2006; Versace et al. 2006). In line with many studies (Gosselin et al. 2005; Harrison and Horne 1997, 1998, 2000; Harrison et al. 2000; Heuer et al. 2004; Jones and Harrison 2001; Killgore et al. 2006; Lingenfelser et al. 1994; McCarthy and Waters 1997; Mckenna et al. 2007; Nilsson et al. 2005; Tsai et al. 2005), results confirm a significant effect of SD on the executive control system. However, other studies did not confirm these findings (Binks et al. 1999; Fallone et al. 2001; Sagaspe et al. 2003). Also when SD studies have evaluated the executive system by using a flanker task, impairment in the conflict control was found by some authors (Tsai et al. 2005), but not by others (Hsieh et al. 2007; Murphy et al. 2006). These inconsistent results could be due to the high inter-subject variability of the effects of SD (Banks and Dinges 2007; Van Dongen et al. 2004). In line with this hypothesis, it was found that, after 48 h of SD, the de-activation of a neural network, including posterior cerebellum, right fusiform gyrus, precuneus, left lingual and inferior temporal gyri, was effective only in participants showing an impairment in memory performance, but not in those able to maintain higher performance (Bell-Mcginty et al. 2004). Equally, Chee and Tan (2010) observed a deactivation of the attention network when participants performed an attention task after SD, specially on participants suffering more from SD. This variability in neural and behavioural responses to SD showing that greater activation of cortical areas during SD was associated with better preserved performance, confirmed also by other studies (Chee et al. 2006, 2008; Chuah and Chee 2008; Vandewalle et al. 2009), may account for many contrasting results in this research area.

In conclusion, the results of this study showed an overall slowing of reaction times in the nocturnal session, indicating a strong decrease in vigilance, and a significant impairment of both orienting and executive control. The sleep deprivation effects on alerting (9 ms) did not reach significance. This result can be mainly ascribed to the light alerting effect of visual warning, or to the fact that alerting did in fact increase interference, rather than decrease it. As matter of the fact, even if we did not find a significant SD effect on alerting, SD affects alerting when participants had to respond to incongruent flankers. If a rather simple task (e.g., a detection task), for which alertness would facilitate responses, had been used perhaps a clear effect of SD on alertness would have been found.

In order to better investigate how the three attentional networks are modulated by tonic alertness, it may be worth repeating the same experimental paradigm by using the modified version of the ANT developed by Callejas et al.

(2004, 2005), who incorporated invalid and valid trials. In this case, we could also be able to evaluate the effect of both components of alerting—i.e., phasic and tonic—on the orienting and executive systems.

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